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PERSISTENCE, RUNS, AND RECURRENCE OF VISIBILITY.(U)

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AFGL-TR-78-0024
ENVIRONMENTAL RESEARCH PAPERS, NO. 624

Persistence, Runs, and Recurrence of Visibility

IVER A. LUND
DONALD D. GRANTHAM

31 January 1978

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METEOROLOGY DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

This report has been reviewed by the ESD Information Office (OI) and is releasable to the National Technical Information Service (NTIS).

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FOR THE COMMANDER

John Howard

Chief Scientist

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER
AFGL-TR-78-0024, AFGL-ERP-624

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

9 Environmental research papers,

4. TITLE (and Subtitle)
6 PERSISTENCE, RUNS, AND RECURRENCE OF VISIBILITY

5. TYPE OF REPORT & PERIOD COVERED
Scientific. Interim.

6. PERFORMING ORG. REPORT NUMBER
ERP No. 624

7. AUTHOR(s)
10 Iver A./ Lund
Donald D./ Grantham

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Air Force Geophysics Laboratory (LYD)
Hanscom AFB,
Massachusetts 01731

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
16 62101F
66700904 17 09

11. CONTROLLING OFFICE NAME AND ADDRESS
Air Force Geophysics Laboratory (LYD)
Hanscom AFB,
Massachusetts 01731

12. REPORT DATE
11 31 Jan[redacted]78

13. NUMBER OF PAGES
12 47 P.

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Persistence
Duration
Recurrence
Visibility
Runs

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A total of 511,056 hourly observations of visibility, taken over a 13-year period at nine stations, was studied to obtain a better understanding of the characteristics of persistence, runs, and recurrence. Each hourly visibility observation was categorized as either greater than or equal to 10 miles, greater than or equal to 5 miles, less than or equal to 3 miles, less than or equal to 1 mile (in summer), or less than or equal to 0.25 mile (in winter). Probabilities of each category were estimated from relative frequencies determined from this large data sample and were compared with some theoretical

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

449 578

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20 (Cont)

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models. The models can be applied to estimate the probability that any visibility category will be observed for sequences of x hours, or more; for exactly x hours; or at time t, and also at time t+x hours.

Preface

The authors are grateful to James F. Atkinson, Leonard J. Natoli, Kenneth C. Zwirble, Analysis and Computer Systems, Inc., John F. Kellaher, Air Force Geophysics Laboratory, and Melinda A. Zouvelos, Student Aid, Lowell University, for expert computational support and to the USAF Environmental Technical Applications Center and the National Weather Service for hourly sky cover data.

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Tables

Persistence, Runs, and Recurrence of Visibility

1. INTRODUCTION

Duration, persistence, runs, and recurrence are all interrelated. For this study, they have been defined as follows: duration-continuous successes; persistence-consecutive successes separated by 1 hour; runs-consecutive successes separated by intervals of 1 hour beginning and ending with a failure; and recurrence-successes occurring at time t and also at time t+x hours

This study is part of a more comprehensive investigation conducted to obtain a better understanding of persistence, runs, and recurrence of weather events. Duration could not be studied because the data were observed at hourly intervals. Of major interest are those weather events which are usually recorded in categories, for example; precipitation recorded as none, light, moderate, or heavy; or sky cover recorded as clear, scattered, broken, or overcast. Persistence, runs, and recurrence of precipitation and sky cover are described in papers by Lund and Grantham.[1,2]

This report includes tables of observed relative frequencies of four visibility categories and models for estimating probabilities of each category. The models

(Received for publication 31 January 1978)

1. Lund, I.A., and Grantham, D.D. (1977a) Persistence, runs, and recurrence of precipitation, J. Appl. Meteor. 16:346-358.
2. Lund, I.A., and Grantham, D.D. (1977b) Persistence, Runs, and Recurrence of Sky Cover, ERP No. 621, AFGL-TR-77-0308.

provide answers to such questions as: What is the probability of observing a sequence of more than 5 hours of visibilities less than or equal to 3 miles (LE3); of observing a run of exactly 5 hours of LE3; and of observing LE3 at time t and also at time t+5 hours? The models require a knowledge of the unconditional probability of the event, in this case a visibility category, and a measure of the temporal correlation between occurrences of visibility categories.

2. DATA

Records of hourly visibility observations taken in winter (December, January, February) and summer (June, July, August) during the 13-year period 1951 through 1963, at the following nine stations, shown in Figure 1, were studied:

LGA	LaGuardia Airport, New York, NY
JFK	Kennedy International Airport, New York, NY
EWR	Newark Airport, NJ
PHL	Philadelphia International Airport, PA
BAL	Baltimore-Washington International Airport, MD
DCA	National Airport, Washington, DC
ADW	Andrews AFB, MD
RIC	Byrd Field, Richmond, VA
RDU	Raleigh-Durham Airport, NC

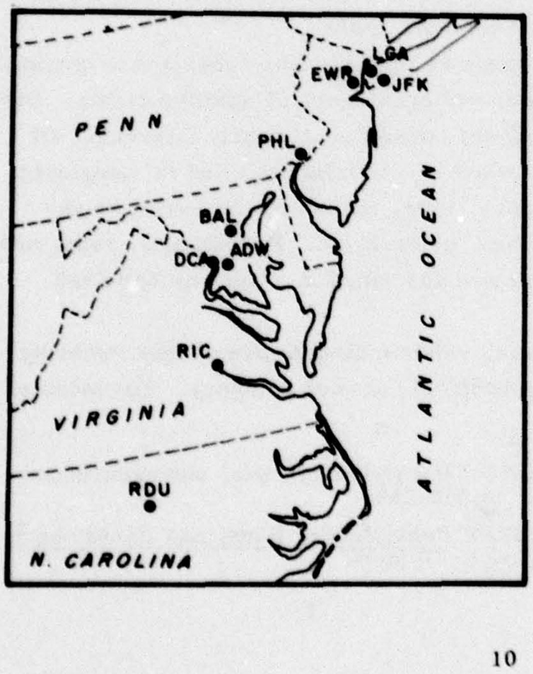

Figure 1. Location of the Nine Stations Whose Winter and Summer Hourly Observations of Visibility Were Studied

Each hour, approximately on the hour, a weather observer at each of the above stations went outdoors to make a regular hourly observation. One of the weather elements recorded is visibility. The Federal Meteorological Handbook[3] describes how the observations are taken. The four visibility categories studied are shown in Table 1. The abbreviations LE and GE stand for "less than or equal to" and "greater than or equal to", respectively. The two ends of the frequency distribution were studied separately to determine whether temporal correlation is a function of visibility.

Table 1. Visibility Categories

Category	Visibility (miles)
1	GE 10.0
2	GE 5.0
3	LE 3.0
4	LE 0.25 (Winter) LE 1.0 (Summer)

3. DATA PROCESSING

Each hourly visibility observation was categorized as follows: GE 10 miles; GE 5 miles; LE 3 miles; LE 1 mile (in summer), or LE 0.25 mile (in winter). Some of the stations had no missing observations, others only a very few. These few observations were filled in by estimating the visibility from observations taken at nearby stations and observations taken before and after the missing observations. There were 28,080 [(24 observations/day) × (90 days/season) × (13 seasons)] observations, in winter, and 28,704 [(24 observations/day) × (92 days/season) × (13 seasons)] observations, in summer, processed for each station.

4. PERSISTENCE

4.1 Observed

The occurrence of a given visibility category was denoted as a success, S, and non-occurrence as a failure, F. The relative frequency of one success, $RF(S_1)$, is found from the data by dividing the number of times the visibility category

3. U.S. Department of Commerce (1975) Federal Meteorological Handbook No. 1, Surface Observations, U.S. Government Printing Office, Washington, DC 309 pp.

occurred, $n(S_1)$, by the sample size N. The relative frequency of two successes in a row, $RF(S_2)$, is found from the data by dividing the number of times a success was followed by a success, $n(S_2)$, by the sample size N minus the end effect, in this case 13, because there were 13 years when the next season's data were not used to determine the visibility on the first hour of the next season. The relative frequency of x successes in a row $RF(S_x)$, is found by dividing the number of times x consecutive successes was observed, $n(S_x)$, by the sample size, N, minus the end effects, in this case 13(x-1).

$$RF(S_x) = \frac{n(S_x)}{N-13(x-1)} \approx \frac{n(S_x)}{N} . \qquad (1)$$

This processing of the data was done for all categories for all nine stations in both winter and summer.

The relative frequency of a success given that x consecutive successes have occurred, $RF(S|S_x)$, is equal to the relative frequency of x+1 consecutive successes, $RF(S_{x+1})$ divided by the relative frequency of x consecutive successes, $RF(S_x)$, that is,

$$RF(S|S_x) = \frac{RF(S_{x+1})}{RF(S_x)} . \qquad (2)$$

The conditional relative frequencies $RF(S|S_x)$ were computed for periods up to 72 hours. Selected values for the first 18 hours are shown for all nine stations and all four visibility categories in Tables 2, 3, 4, and 5. The median relative frequencies are indicated with asterisks.

The first column in each of the tables gives $RF(S|S_o)$ which is defined as RF(S), the unconditional relative frequency of the given visibility category. Although both the unconditional and conditional relative frequencies vary from station to station, there is often no consistent pattern to the variations. It was subjectively decided to assume that the data from all stations were drawn from the same sample and to use the median values to obtain estimates of the conditional probabilities, $\hat{P}(S|S_x)$, required for obtaining estimates of probabilities of x+1 consecutive successes, $\hat{P}(S_{x+1})$.

Table 2. Relative Frequencies of Success Given that x Consecutive Successes Have Occurred, $RF(S|S_x)$, Obtained From the Data Sample When GE 10 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	x (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.4288	.926	.930	.934	.935	.936	.936	.936	.937	.936	.935	.934	.933	.932	.932	.933	.932	.931	.931
	JFK	.4980	.923	.930	.934	.937	.938	.938	.938	.939	.940	.939	.940	.940	.941	.940	.939	.938	.939	.940
	EWR	.5036	.934	.940	.943	.946	.948	.949	.951	.953*	.954*	.954*	.954*	.955*	.955*	.955*	.955*	.955*	.953	.952
	PHL	.4729	.933	.937	.941	.942	.944	.946	.948	.948	.949	.949	.950	.950	.952	.953	.953	.954	.953	.953
	BAL	.5581	.948	.952	.954	.957	.958	.960	.960	.960	.960	.961	.961	.961	.962	.963	.962	.962	.963	.963
	ADW	.5397*	.947*	.951*	.953*	.955	.956	.957	.959	.959	.959	.960	.960	.960	.960	.960	.961	.962	.963	.963
	DCA	.6024	.949	.952	.955	.956	.957	.958	.959	.960	.961	.962	.962	.962	.962	.962	.962	.962	.962	.962
	RIC	.5655	.950	.952	.953*	.954*	.953*	.952*	.953*	.953*	.953	.953	.953	.954	.954	.954	.954	.954	.955*	.956*
	RDU	.7208	.959	.962	.964	.966	.966	.967	.967	.967	.968	.968	.968	.968	.968	.969	.969	.970	.970	.970
Summer	LGA	.3981	.913	.922	.927	.930	.932	.935*	.937*	.939	.940	.941	.941	.943	.943	.943	.945	.947	.949	.950
	JFK	.4764*	.916	.927*	.934	.937	.939	.941	.942	.944	.943	.944	.944	.945	.944	.945	.945	.947	.947	.948
	EWR	.4497	.905	.913	.917	.920	.923	.925	.924	.924	.926	.926	.927	.927	.927	.928	.929	.929	.931	.935
	PHL	.3729	.892	.900	.905	.908	.910	.912	.912	.914	.914	.914	.915	.915	.916	.919	.923	.923	.924	.926
	BAL	.5243	.924	.927*	.932	.934	.937	.937	.939	.939	.941	.943	.942	.943	.943	.343	.945	.947	.948	.948
	ADW	.4859	.919*	.924	.926	.928	.931	.932	.933	.932	.933	.934	.934	.935	.935	.936	.936	.937	.939*	.941*
	DCA	.6233	.932	.936	.938	.939	.940	.941	.941	.942	.942	.944	.944	.944	.944	.945	.945	.946	.946	.946
	RIC	.4744	.972	.928	.930*	.932*	.933*	.933	.933	.933	.931	.932	.931	.930	.931	.932	.932	.933	.936	.938
	RDU	.6679	.931	.935	.937	.938	.938	.938	.937*	.938*	.939*	.938*	.937*	.937*	.936*	.937*	.937*	.938*	.939*	.940

Table 3. Relative Frequencies of Success Given that x Consecutive Successes Have Occurred, $RF(S|S_x)$, Obtained From the Data Sample When GE 5 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	x (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.7510	.954	.960	.964	.965	.966	.967	.967	.967	.967	.968	.968	.968	.968	.968	.969	.969	.969	.969
	JFK	.7917*	.959	.965	.968	.969	.970	.971	.972	.972	.973	.973	.972	.973	.972	.972	.973	.973	.973	.973
	EWR	.7433	.956	.961	.964	.966	.967	.968	.969	.969	.970	.971	.971	.971	.971	.971	.972	.971	.971	.971
	PHL	.7472	.957	.962	.965	.967	.968	.968	.968	.968	.969	.969	.969	.969	.970	.970	.970	.970	.971	.971
	BAL	.7882	.969	.972	.974	.976	.976	.976	.977	.978	.978	.978	.978	.978	.978*	.978*	.979	.979	.980	.980
	ADW	.8214	.976	.978	.980	.981	.981	.981	.982	.982	.982	.982	.982	.982	.982	.982	.982	.983	.983	.983
	DCA	.8088	.967*	.971*	.973*	.974*	.974*	.975*	.975*	.976*	.976*	.976*	.977*	.977*	.978*	.978*	.978*	.978*	.978*	.978*
	RIC	.8354	.975	.977	.978	.979	.979	.980	.980	.980	.980	.980	.980	.980	.980	.980	.980	.981	.981	.981
	RDU	.8786	.980	.982	.984	.985	.985	.986	.986	.986	.986	.986	.987	.987	.987	.987	.987	.987	.988	.988
Summer	LGA	.7832	.951	.956	.958	.960	.961	.961	.961	.962	.963	.964	.964	.964	.964	.964	.964	.964	.965	.966
	JFK	.7982	.951	.957	.959	.961	.962	.963	.964	.964	.965	.966	.966	.966	.967	.967	.967	.968	.968	.969
	EWR	.7872	.950	.954	.956	.957	.958	.959	.959	.959	.959	.959	.960	.959	.959	.959	.959	.959	.959	.960
	PHL	.7679	.944	.949	.952	.954	.954	.954	.954	.954	.954	.954	.954	.954	.954	.955	.954	.955	.956	.957
	BAL	.8634*	.968*	.970*	.972*	.972*	.973*	.973*	.974*	.974*	.974*	.974*	.974*	.974*	.975*	.974*	.975*	.975*	.975*	.976*
	ADW	.8704	.969	.971	.972*	.973	.973*	.974	.974*	.975	.975	.976	.976	.976	.977	.977	.978	.978	.978	.978
	DCA	.9217	.977	.979	.980	.980	.981	.981	.982	.982	.982	.982	.982	.982	.982	.983	.983	.983	.983	.983
	RIC	.8721	.970	.971	.972*	.973	.974	.974	.974*	.975	.975	.975	.975	.975	.975*	.976	.976	.976	.976	.977
	RDU	.9117	.972	.974	.976	.976	.976	.976	.976	.976	.976	.977	.977	.977	.977	.976	.976	.976	.977	.977

Table 4. Relative Frequencies of Success Given that x Consecutive Successes Have Occurred, RF($S|S_x$), Obtained From Data Sample When LE 3 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	x (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.1842	.829	.848	.860	.866	.872	.875	.875	.878	.876	.881	.884	.886	.884	.886	.891	.890	.896	.895
	JFK	.1532*	.818	.840	.853	.863	.871	.872	.875	.878	.882	.884	.888	.892	.895	.896	.892	.891	.884	.889
	EWR	.2013	.853*	.868*	.879*	.883	.886	.888*	.891	.893	.895	.894*	.897	.903	.906	.906	.906	.906	.909	.910
	PHL	.1966	.856	.875	.883	.889	.891	.896	.894	.893	.899	.899	.904	.904	.900*	.903*	.904*	.904*	.906*	.902
	BAL	.1677	.877	.890	.898	.902	.900	.900	.902	.902	.903	.906	.907	.906	.904	.912	.908	.909	.910	.912
	ADW	.1499	.884	.895	.900	.900	.901	.902	.906	.907	.908	.907	.911	.913	.912	.906	.908	.905	.906*	.901*
	DCA	.1512	.834	.850	.860	.863	.869	.876	.883	.884	.887	.886	.886	.883	.885	.886	.881	.831	.876	.885
	RIC	.1325	.864	.872	.877	.882*	.885*	.888*	.890*	.892*	.889*	.894*	.896*	.901*	.903	.913	.909	.916	.913	.914
	RDU	.09765	.832	.850	.862	.866	.870	.871	.875	.872	.876	.874	.875	.873	.873	.867	.865	.866	.881	.882
Summer	LGA	.1369	.775	.798	.807	.805	.810	.818	.820	.825	.833*	.825	.832*	.849	.852	.850	.847	.848*	.888	.887
	JFK	.1355	.774	.799	.810	.811	.822	.820	.817*	.823*	.837	.845	.844	.846*	.843*	.833	.843	.846	.852	.852
	EWR	.1459	.776	.791	.799	.802*	.805*	.806*	.809	.813	.818	.818	.814	.820	.835	.829	.844*	.859	.867*	.854*
	PHL	.1586	.769*	.785*	.790	.788	.788	.783	.792	.791	.792	.806	.818	.816	.816	.835	.834	.838	.822	.829
	BAL	.08720*	.777	.794	.798	.813	.813	.828	.832	.832	.837	.846	.855	.862	.881	.879	.878	.904	.913	.912
	ADW	.08462	.746	.786*	.797*	.811	.810	.816	.828	.837	.851	.847	.829	.841	.840	.843*	.840	.841	.830	.852
	DCA	.04776	.673	.717	.724	.724	.761	.792	.832	.856	.866	.853	.854	.851	.887	.873	.919	.912	.923	.917
	RIC	.08114	.759	.778	.785	.794	.791	.792	.803	.822	.828	.840*	.854	.862	.874	.868	.891	.902	.910	.931
	RDU	.05999	.657	.706	.726	.748	.760	.770	.762	.784	.801	.800	.800	.812	.785	.804	.756	.774	.750	.722

Table 5. Relative Frequencies of Success Given that x Consecutive Successes Have Occurred, RF($S|S_x$), Obtained from the Data Sample When LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer is Considered a Success. Median values are identified with asterisks

Season	Station	x (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.007870	.719*	.742	.780	.804	.797	.797	.787	.811	.800	.833	.800	.750	.667	.625*	.400*			
	JFK	.01627	.685	.728	.763	.782	.809	.782	.756*	.754	.694	.735	.760	.737	.643*	.667	.500	.333		
	EWR	.02189	.682	.733*	.773	.778	.807	.818	.792	.772	.727	.750*	.708*	.706*	.667	.625*	.400*			
	PHL	.01912	.745	.785	.777	.770*	.771*	.752*	.761	.759*	.762	.750*	.750	.778	.714	.667	.600	.667	.500	
	BAL	.02639	.753	.790	.805	.806	.811	.806	.802	.807	.802	.794	.753	.759	.773	.765	.769	.750	.733	.818
	ADW	.02696	.729	.748	.768*	.757	.746	.737	.750	.788	.769	.750*	.689	.581	.500	.556	.400*	.500		
	DCA	.009366	.604	.635	.663	.716	.688	.727	.667	.687	.727	.750*	.667	.500	.500					
	RIC	.01296	.720	.721	.730	.717	.717	.676	.646	.742	.739*	.765	.692	.667	.500	.333				
	RDU	.01460*	.685	.680	.686	.718	.755	.690	.694	.735	.640	.625	.700	.571	.500	.500				
Summer	LGA	.01115	.572	.623	.579	.606	.600	.542	.461	.333	.500									
	JFK	.02139	.655	.684	.684	.686	.651	.643	.630	.647	.682	.667	.600	.500	.667	.500				
	EWR	.01944	.599	.641	.673	.646	.699	.708	.761	.771	.704	.684	.769	.700	.714	.600	.333			
	PHL	.01651*	.584	.639*	.621*	.573	.571	.556*	.600	.667	.750	.667	.500*	.500						
	BAL	.01348	.589*	.601	.591	.580	.489	.435	.400	.250										
	ADW	.01561	.605	.646	.674	.644	.645	.571	.679	.684	.769	.800	.750	.667	.500	.500				
	DCA	.001881	.352	.368	.143															
	RIC	.01975	.615	.650	.634	.611*	.602*	.547	.552	.437	.571*	.500*	.500*							
	RDU	.01968	.573	.599	.613	.622	.608	.578	.577*	.533*	.375									

The median values of $RF(S|S_x)$ for winter and summer are shown in Figure 2 for periods up to 18 hours. The median relative frequency, RF(S), of the most frequently occurring category, GE 5 miles was 0.7917 in winter and 0.8634 in summer. Because this is a frequently occurring category there were many long sequences of successes. The median conditional relative frequencies for GE 5, given in Table 6 and shown as x's in Figure 2, increase in magnitude for 13 hours in winter and 15 hours in summer. They never vary significantly, that is, by more than 0.001 for the next few hours after hour 15, therefore the estimated conditional probabilities are regarded as constant after hour 15. The conditional relative frequencies of the less frequently occurring categories are more variable as expected but they never depart from the hour 15 conditional relative frequencies by more than 0.023.

Sample relative frequencies of x consecutive successes, $RF(S_x)$, obtained from the data sample, are given in Tables, 7, 8, 9, and 10. All of the relative frequencies for hours 1 through 70 are shown in Figures 3, 4, 5, and 6.

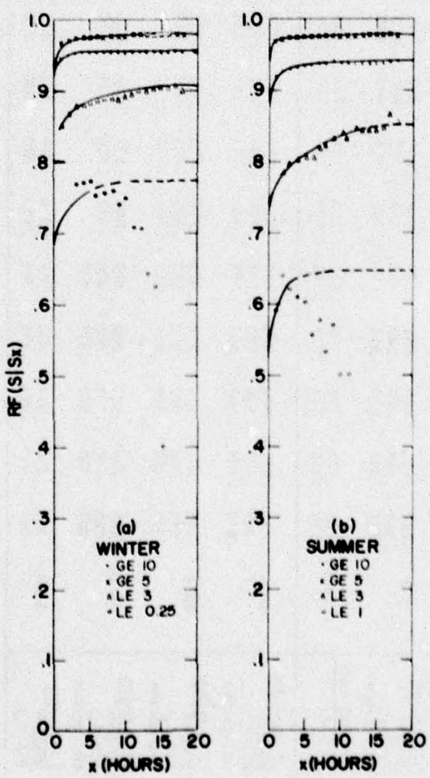

Figure 2. Relative Frequencies of Success, Given x Hours of Consecutive Successes Have Occurred, in Winter (a) and Summer (b). The curves were subjectively drawn. The dashed portions of the curves are based on fewer than 30 cases

Table 6. Median Values of RF($S|S_x$) Obtained From the Data Sample (Tables 2, 3, 4, and 5) and Probability Estimates $\hat{P}(S|S_x)$ Determined From Subjectively Drawn Curves of the Medians Shown in Figure 2. Also shown are some probability estimates obtained from Gringorten's model

Season		x (Hours)																		
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	GE 10 miles																			
	Median	.5397	.947	.951	.953	.954	.953	.952	.953	.953	.954	.954	.954	.955	.955	.955	.955	.955	.955	.956
	$\hat{P}(S\|S_x)$		.947	.951	.952	.953	.953	.953	.953	.953	.954	.954	.954	.955	.955	.955	.955	.955	.955	.955
	Gringorten		.871	.897	.927	.935	.937	.938	.939	.939	.940	.942	.943	.945	.947	.948	.949	.950	.950	.950
	GE 5 miles																			
	Median	.7917	.967	.971	.973	.974	.974	.975	.975	.976	.976	.976	.977	.977	.978	.978	.978	.978	.978	.978
	$\hat{P}(S\|S_x)$		.967	.971	.973	.974	.974	.975	.975	.976	.976	.976	.977	.977	.978	.978	.978	.978	.978	.978
	Gringorten		.902	.952	.960	.965	.968	.970	.972	.973	.974	.974	.975	.975	.975	.976	.976	.977	.977	.978
	LE 3 miles																			
	Median	.1532	.853	.868	.879	.882	.885	.888	.890	.892	.889	.894	.896	.901	.900	.903	.904	.904	.906	.901
	$P(S\|S_x)$		.853	.868	.879	.882	.886	.888	.890	.892	.896	.898	.900	.901	.902	.903	.904	.904	.904	.904
	Gringorten		.594	.813	.840	.855	.865	.870	.875	.881	.885	.889	.892	.894	.892	.889	.885	.880	.872	.865
	LE 0.25 mile																			
	Median	.01460	.719	.733	.768	.770	.771	.752	.756	.759	.739	.750	.708	.706	.643	.625	.400			
	$P(S\|S_x)$		.719	.733	.748	.756	.761	.765	.768	.770	.771	.771	.772	.772	.772	.772	.772	.772	.772	.772
Summer	GE 10 miles																			
	Median	.4764	.919	.927	.930	.932	.933	.935	.937	.938	.939	.938	.937	.936	.936	.937	.937	.938	.939	.941
	$\hat{P}(S\|S_x)$		.919	.927	.930	.932	.933	.935	.936	.937	.937	.937	.938	.938	.938	.938	.939	.939	.939	.939
	Gringorten		.819	.861	.893	.897	.903	.907	.911	.913	.914	.917	.919	.921	.922	.923	.924	.924	.925	.925
	GE 5 miles																			
	Median	.8634	.968	.970	.972	.972	.973	.973	.974	.974	.974	.974	.974	.974	.975	.974	.975	.975	.975	.976
	$\hat{P}(S\|S_x)$		.968	.970	.972	.972	.973	.973	.974	.974	.974	.974	.974	.974	.974	.975	.975	.975	.975	.975
	Gringorten		.917	.953	.962	.966	.969	.971	.972	.973	.974	.975	.975	.975	.975	.975	.974	.973	.971	.967
	LE 3 miles																			
	Median	.08720	.769	.786	.797	.802	.805	.806	.817	.823	.833	.840	.832	.846	.843	.843	.844	.848	.867	.854
	$\hat{P}(S\|S_x)$		.769	.786	.793	.802	.808	.815	.820	.826	.832	.835	.840	.843	.845	.847	.850	.850	.850	.850
	Gringorten		.607	.755	.800	.824	.836													
	LE 1 mile																			
	Median	.01651	.589	.639	.621	.611	.602	.556	.577	.533	.571	.500	.500							
	$\hat{P}(S\|S_x)$		.589	.615	.628	.635	.639	.639	.640	.640	.640	.640	.640	.640	.640	.640	.640	.640	.640	.640

Table 7. Relative Frequencies of x Consecutive Successes, $RF(S_x)$, Obtained From the Date Sample When GE 10 Miles Visibility is Considered a Success. Median values are identified with asterisks

		x (Hours)														
Season	Station	1	2	3	4	5	6	9	12	18	24	30	36	48	60	72
Winter	LGA	.429	.397	.370	.345	.323	.302	.248	.203	.133	.0881	.0615	.0402	.0175	.00853	.00350
	JFK	.498	.459	.427	.399	.374	.351	.290	.241	.166	.115	.0810	.0555	.0258	.0124	.00503
	EWR	.504	.470	.442	.417	.394	.374	.321	.279	.212	.158	.117	.0827	.0425	.0223	.0131
	PHL	.473	.441	.414	.389	.366	.346	.294	.252	.188	.141	.105	.0775	.0415	.0239	.0147
	BAL	.558	.529	.504	.481	.460	.441	.390	.346	.274	.219	.177	.142	.0855	.0499	.0293
	ADW	.540*	.511*	.486*	.463*	.443*	.423*	.373*	.329*	.259	.210	.173	.140	.0898	.0573	.0356
	DCA	.602	.571	.544	.519	.497	.475	.420	.373	.295	.237	.192	.155	.0963	.0604	.0396
	RIC	.565	.537	.511	.487	.465	.443	.383	.332	.251*	.195*	.157*	.125*	.0762*	.0466*	.0281*
	RDU	.721	.691	.665	.641	.619	.599	.542	.491	.407	.344	.296	.253	.184	.132	.0915
	Median	.540	.511	.486	.463	.443	.423	.373	.329	.251	.195	.157	.125	.0762	.0466	.0281
Summer	LGA	.398	.363	.335	.311	.289	.269	.222	.184	.131	.0981	.0739	.0552	.0295	.0152	.00719
	JFK	.476*	.436	.405	.378	.354*	.333	.278	.234	.167	.123	.0908	.0663	.0342*	.0166	.00761
	EWR	.450	.407	.371	.341	.314	.290	.229	.182	.117	.0834	.0615	.0439	.0200	.00915	.00405
	PHL	.373	.333	.300	.271	.246	.224	.171	.130	.0791	.0542	.0400	.0289	.0138	.00778	.00416
	BAL	.524	.485	.449	.419	.391	.367	.303	.253	.180	.137	.109	.0870	.0544	.0345	.0211
	ADW	.486	.447	.413	.382	.355	.330*	.268	.218*	.147*	.107*	.0824*	.0633*	.0385	.0251	.0157
	DCA	.623	.581	.544	.510	.480	.451	.376	.316	.225	.168	.134	.106	.0663	.0435	.0268
	RIC	.474	.440*	.408*	.379*	.354	.330	.268*	.216	.142	.101	.0772	.0579	.0304	.0179*	.0108*
	RDU	.668	.622	.582	.545	.512	.480	.396	.327	.222	.164	.133	.108	.0707	.0500	.0360
	Median	.476	.440	.408	.379	.354	.330	.268	.218	.147	.107	.0824	.0633	.0342	.0179	.0108

Table 8. Relative Frequencies of x Consecutive Successes, $RF(S_x)$, Obtained From the Data Sample When GE 5 Miles Visibility is Considered a Success. Median values are identified with asterisks

		x (Hours)														
Season	Station	1	2	3	4	5	6	9	12	18	24	30	36	48	60	72
Winter	LGA	.751	.717	.688	.663	.640	.619	.560	.508	.419	.348	.288	.234	.154	.0998	.0600
	JFK	.792*	.759	.733	.709	.688	.668	.613	.564	.478	.407	.347	.293	.208	.149	.105
	EWR	.743	.711	.683	.658	.636	.615	.559	.511	.430	.361	.302	.251	.170	.113	.0742
	PHL	.747	.715	.688	.664	.642	.621	.564	.513	.427	.360	.306	.257	.179	.124	.0855
	BAL	.788	.764*	.742*	.723*	.706*	.689*	.643*	.602*	.530*	.467	.413	.363	.277	.207*	.154*
	ADW	.821	.801	.784	.768	.753	.739	.700	.662	.596	.538	.486	.439	.354	.284	.226
	DCA	.809	.782	.760	.739	.720	.702	.651	.606	.530*	.466*	.411*	.360*	.274*	.207*	.156
	RIC	.835	.815	.796	.778	.762	.746	.702	.661	.587	.526	.473	.425	.344	.279	.223
	RDU	.879	.861	.846	.832	.820	.808	.774	.743	.688	.642	.599	.558	.480	.412	.352
	Median	.792	.764	.742	.723	.706	.689	.643	.602	.530	.466	.411	.360	.274	.207	.154
Summer	LGA	.783	.745	.712	.682	.655	.62[illegible]	.560	.501	.403	.332	.279	.231	.157	.108	.0718
	JFK	.798	.759	.727	.697	.670	.645	.577	.519	.426	.358	.306	.259	.186	.138	.101
	EWR	.787	.748	.714	.683	.653	.626	.552	.488	.380	.307	.259	.216	.146	.103	.0701
	PHL	.768	.725	.688	.655	.625	.596	.518	.451	.341	.272	.225	.184	.120	.0810	.0523
	BAL	.863*	.836*	.811*	.789*	.767*	.746*	.688*	.636*	.546*	.478*	.428*	.384*	.309*	.251*	.201*
	ADW	.870	.844	.819	.796	.775	.754	.698	.648	.565	.501	.451	.404	.326	.265	.213
	DCA	.922	.900	.881	.863	.846	.830	.785	.744	.670	.613	.567	.526	.452	.390	.334
	RIC	.872	.846	.822	.799	.778	.757	.701	.650	.560	.494	.445	.399	.326	.273	.229
	RDU	.912	.837	.864	.843	.823	.803	.748	.697	.604	.535	.484	.437	.356	.296	.246
	Median	.863	.836	.811	.789	.767	.746	.688	.636	.546	.478	.428	.384	.309	.251	.201

Table 9. Relative Frequencies of x Consecutive Successes, $RF(S_x)$, Obtained From the Data Sample When LE 3 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	x (Hours)														
		1	2	3	4	5	6	9	12	18	24	30	36	48	60	72
Winter	LGA	.184	.153	.129	.111	.0964	.0841*	.0565*	.0386*	.0190	.0107	.00585	.00275	.000464	.0000357	0
	JFK	.153*	.125	.105	.0898	.0775	.0675	.0452	.0313	.0157	.00809	.00428	.00210	.000321	0	0
	EWR	.210	.172	.149	.131	.116	.102	.0724	.0520	.0288	.0166	.00948	.00510*	.00164*	.000286*	0
	PHL	.197	.168	.147	.130	.116	.103	.0738	.0539	.0294	.0167	.00995	.00588	.00264	.000785	.000143
	BAL	.168	.147	.131	.117	.106	.0955	.0699	.0519	.0291	.0178	.0121	.00838	.00364	.000607	0
	ADW	.150	.133*	.119*	.107*	.0961*	.0866	.0642	.0482	.0271	.0148	.00984	.00642	.00264	.000607	0
	DCA	.151	.126	.107	.0922	.0796	.0692	.0473	.0329	.0155	.00830	.00474	.00239	.000321	0	0
	RIC	.132	.115	.100	.0876	.0773	.0684	.0482	.0343	.0194*	.0117*	.00770*	.00535	.00182	.000286	0
	RDU	.0976	.0812	.0691	.0595	.0515	.0448	.0298	.0200	.0873	.00367	.00160	.000464	0	0	0
	Median	.153	.133	.119	.107	.0961	.0841	.0565	.0386	.0914	.0117	.00770	.00510	.00164	.000286	0
Summer	LGA	.137	.106	.0846	.0683	.0550	.0445	.0247	.0141	.00554	.00282	.00143	.000977	.000314	0	0
	JFK	.135	.105	.0839	.0680	.0552	.0453	.0250	.0149	.00540	.00241	.00146	.000907	.000488	.0000698	0
	EWR	.146	.113	.0897	.0716	.0575	.0463	.0246	.0134	.00478	.00178*	.000698	.000279*	0	0	0
	PHL	.159	.122	.0959	.0758	.0597	.0471	.0231	.0121	.00387*	.00132	.000453	0	0	0	0
	BAL	.0872*	.0677*	.0538*	.0429*	.0349*	.0284*	.0163*	.00986*	.00478	.00272	.00146	.000942	.000349	0	0
	ADW	.0846	.0632	.0496	.0396	.0321	.0260	.0147	.00878	.00307	.00139	.000732*	.000244	0	0	0
	DCA	.0478	.0322	.0231	.0167	.0121	.0920	.00519	.00328	.00167	.00101	.000523	.000279	0	0	0
	RIC	.0811	.0616	.0479	.0376	.0299	.0237	.0124	.00735	.00352	.00206	.000976	.000732	.000314	0	0
	RDU	.0600	.0405	.0286	.0208	.0155	.0118	.00544	.00279	.000628	.000174	0	0	0	0	0
	Median	.0872	.0677	.0538	.0429	.0349	.0284	.0163	.00986	.00387	.00178	.000732	.000279	0	0	0

Table 10. Relative Frequencies of x Consecutive Successes, $RF(S_x)$, Obtained From the Data Sample When LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer is Considered a Success. Median values are identified with asterisks

Season	Station	x (Hours) 1	2	3	4	5	6	9	12	18	24
Winter	LGA	.00787	.00566	.00420	.00328	.00264	.00210	.00107	.000570	0	0
	JFK	.0163	.0111	.00812	.00620	.00484	.00392	.00174	.000677	0	0
	EWR	.0129	.00880	.00645	.00499*	.00388*	.00313*	.00157*	.000606*	0	0
	PHL	.0191	.0142	.0112	.00869	.00670	.00516	.00224	.000962	.0000713	0
	BAL	.0264	.0199	.0157	.0126	.0102	.00826	.00431	.00207	.000392	.0000713
	ADW	.0270	.0197	.0147	.0113	.00855	.00638	.00278	.00110	0	0
	DCA	.00937	.00566	.00360	.00239	.00171	.00117	.000392	.000142	0	0
	RIC	.0130	.00933	.00673	.00491	.00353	.00253	.000819	.000321	0	0
	RDU	.0146*	.0100*	.00680*	.00467	.00335	.00253	.000891	.000249	0	0
	Median	.0146	.0100	.00680	.00499	.00388	.00313	.00157	.00606	0	0
Summer	LGA	.0111	.00638	.00397	.00230	.00139	.000836	.0000697	0		
	JFK	.0214	.0140	.00958	.00655	.00449	.00293	.000767	.000209		
	EWR	.0194	.0116	.00746	.00502	.00324	.00226	.000941	.000348		
	PHL	.0165*	.00965*	.00617*	.00383	.00219	.00125	.000279*	.0000697		
	BAL	.0135	.00794	.00477	.00282	.00164	.000801	.0000348	0		
	ADW	.0156	.00944	.00610	.00411*	.00265	.99171	.000453	.000209		
	DCA	.00188	.000662	.000244	.0000348	0	0	0	0		
	RIC	.0197	.0122	.00791	.00502	.00307	.00185	.000244	.0000349*		
	RDU	.0197	.0113	.00676	.00415	.00258*	.00157*	.000279*	0		
	Median	.0165	.00965	.00617	.00411	.00258	.00157	.000279	.0000349		

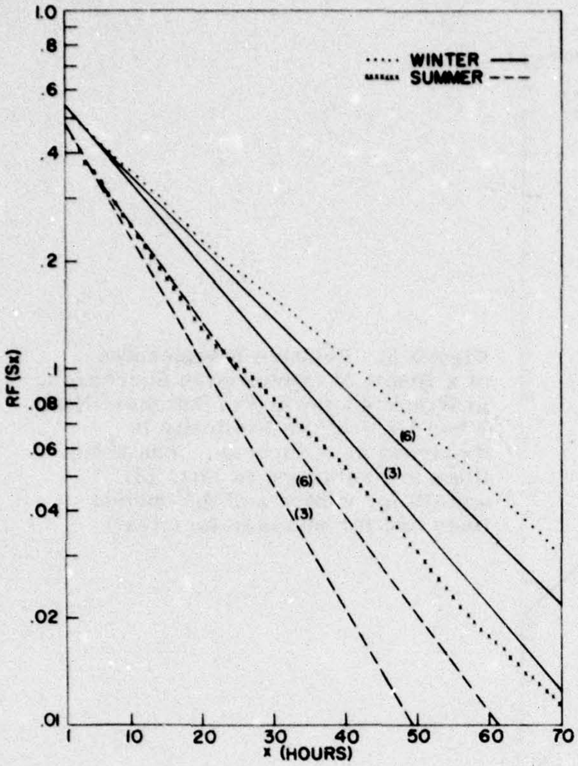

Figure 3. Relative Frequencies of x Hours of Consecutive Successes, in Winter (dots) and in Summer (X's), When GE 10 Miles Visibility is Regarded as a Success. The solid lines are solutions to Eqs. (3) and (6) for winter and the dashed lines are for summer (see text)

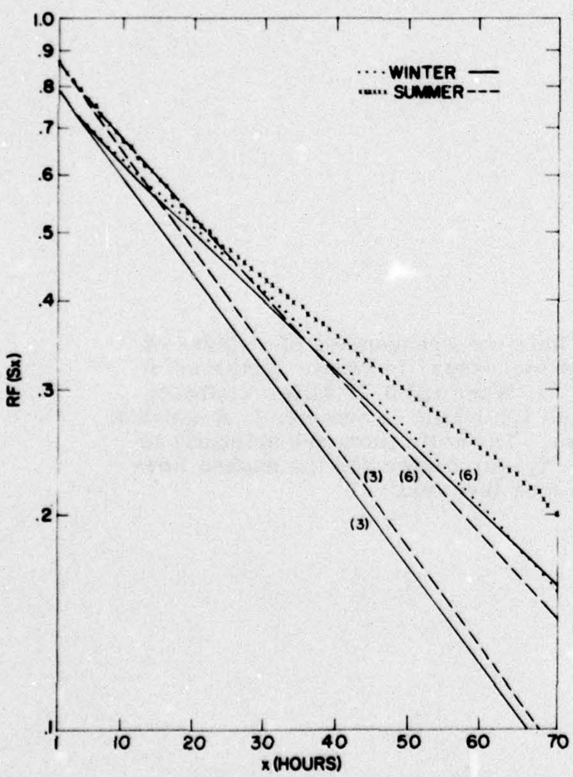

Figure 4. Relative Frequencies of x Hours of Consecutive Successes, in Winter (dots) and in Summer (X's) When GE 5 Miles Visibility is Regarded as a Success. The solid lines are solutions to Eqs. (3) and (6) for winter and the dashed lines are for summer (see text)

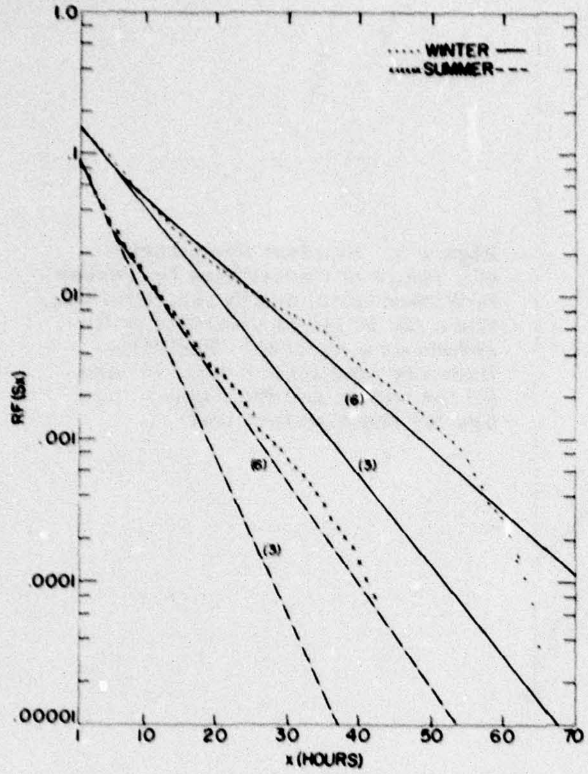

Figure 5. Relative Frequencies of x Hours of Consecutive Successes, in Winter (dots) and in Summer (X's), When LE 3 Miles Visibility is Regarded as a Success. The solid lines are solutions to Eqs. (3) and (6) for winter and the dashed lines are for summer (see text)

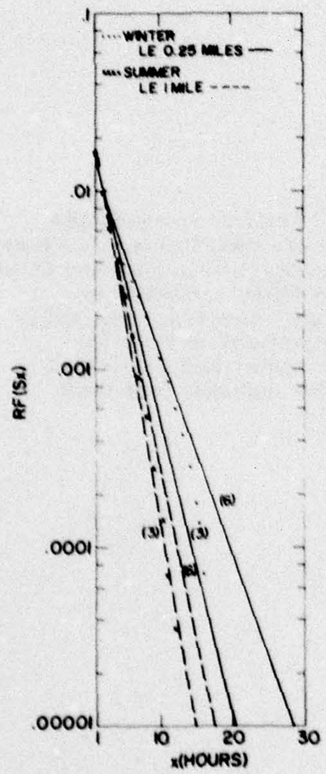

Figure 6. Relative Frequencies of x Hours of Consecutive Successes, in Winter (dots) and in Summer (X's), When LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer is Regarded as a Success. The solid lines are solutions to Eqs. (3) and (6) for winter and the dashed lines are for summer (see text)

4.2 Modeled

The probability of a sequence of x hours of successes is sometimes estimated with the following first order Markov chain:

$$\hat{P}(S_x) = P(S)\,[P(S|S_1)]^{x-1} \tag{3}$$

where $P(S|S_1)$ is the probability of a success given a success has occurred and x equals the number of hours.

The relative frequencies RF(S) and $RF(S|S_1)$, obtained from the data, are given in the first two columns in Tables 2 to 5. The estimated conditional probabilities, $\hat{P}(S|S_1)$, shown in Table 6, were used to test Eq. (3). The model fit the observed values, within a few percent, for the first few hours but there were large differences between the model estimates and corresponding sample relative frequencies when probabilities of sequences of successes longer than a few hours were estimated. Figures 3 to 6 illustrate differences between model estimates and observed relative frequencies when the nine station median relative frequencies are used to represent the sample values. These figures illustrate the failure of Eq. (3) to adequately estimate long sequences of successes. For example, note the large departures of the first order Markov model estimates, labelled (3), from the sample relative frequencies of visibility LE 3 miles shown in Figure 5.

To improve the model given in Eq. (3) the following axiomatic expressions can be estimated 2 and x hours of consecutive successes, respectively:

$$P'(S_2) = P(S)\,P(S|S_1) \tag{4}$$

$$P'(S_x) = P(S)\,P(S|S_1)\ldots P(S|S_{x-1}) \qquad x \geq 3 \tag{5}$$

where $P(S|S_1)$ is the probability of a success given that a success occurred the previous hour, and $P(S|S_{x-1})$ is the probability of a success following (x-1) hours of unbroken successes.

The probabilities required for the solution of Eq. (5) were estimated from the relative frequencies and it was assumed that the conditional probabilities were always constant beyond 15 hours. To estimate joint probabilities Eq. (5) was expressed as follows:

$$\left.\begin{aligned}
\hat{P}'(S_x) &= \hat{P}(S)\,\hat{P}(S|S_{x-1}) && x=2\\
\hat{P}'(S_x) &= \hat{P}(S)\,\hat{P}(S|S_1)\ldots\ldots\hat{P}(S|S_{x-1}) && 3 \leq x \leq 15\\
\hat{P}'(S_x) &= \hat{P}(S)\,\hat{P}(S|S_1)\ldots\ldots\hat{P}(S|S_{14})\,[\,\hat{P}(S|S_{15})]^{x-15} && x \geq 16
\end{aligned}\right\} \tag{6}$$

Curves were drawn for the points in Figure 2 and estimates of $P(S|S_x)$ for use in Eq. (6) were obtained from the curves. These values are given in Table 6 in the rows labelled $\hat{P}(S|S_x)$. With the exception of the low visibility category, the conditional relative frequencies increase fairly steadily but at a slower rate as x approaches 15 hours. As stated earlier, the conditional relative frequencies remain almost constant after 15 hours. Because the low visibility category occurs less than 2% of the time, the shape of the curves is uncertain. The curves are dashed where relative frequencies are based on less than 30 cases to emphasize the uncertainty.

Solutions to Eq. (6), are shown by the curves in Figures 3 to 6. They are in better agreement with the relative frequencies than curves based on Eq. (3). This must be the case, because the probability estimates for Eq. (6) are based more closely on the relative frequencies. Modeling is involved in the smoothing of the relative frequencies and in the assumption that $P(S|S_x)$ is constant beyond 15 hours.

Gringorten[4] simulated probability distributions by a Monte Carlo exercise and prepared charts for use in estimating the duration of weather events. These charts were used to estimate conditional probabilities of the four categories of visibility. Hour-to-hour correlation for this application of Gringorten's method was assumed to be 0.950 in winter and 0.932 in summer. Table 6 shows that the conditional probability estimates obtained by Gringorten's method are usually lower than those obtained from the data. This is consistent with expectations because they represent duration probabilities, not persistence probabilities. One shortcoming of the method is that it is graphical. It is difficult to estimate the probabilities from the charts. A promising analytical method described in the treatise by Keilson and Ross[5] needs further development before it can be applied to this problem. In the absence of conditional relative frequencies obtained from large data samples, Gringorten's method can provide suitable estimates of the probabilities required for the solution of Eq. (6). Because a large sample of data was available for this study, a smooth subjective fit to the relative frequencies was used to estimate the required probabilities.

Table 11 summarizes some of the information obtainable from Eq. (6) and the the data shown in Figures 3 to 6. It shows the number of hours, x, that each of the four visibility categories was estimated, and observed, to persist, at six probability levels based on $\hat{P}(S_x)$ and RF (S_x), respectively. For example, line 1 of Table 11 shows that GE 10 miles visibility has a climatic occurrence probability

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4. Gringorten, I. I. (1966) A stochastic model of the frequency and duration of weather events, J. Appl. Meteor. 5:606-624.

5. Keilson, J., and Ross, H. F. (1975) Passage Time Distributions for Gaussian Markov (Ornstein-Uhlenbeck) Statistical Processes. Selected Tables in Mathematical Statistics Vol. III. American Mathematical Society, Providence, Rhode Island, pp.233-327.

of 0.5397, in winter, and that 50% of the time GE 10 would be expected to be observed for at least 2 hours. Approximately 25% of the time GE 10 is expected to be observed for at least 17 hours. GE 10 is expected to persist for 37, 52, >72, and >72 hours; 10%, 5%, 1%, and 0.1% of the time, respectively, as can be seen from the solid curve based on Eq. (6) shown in Figure 3. The corresponding observed values are shown in parentheses in the table.

The values given in Tables 11 and 12 are for eastcoast stations. They apply elsewhere only to the extent that the probability of the event and the hour-to-hour correlation is the same.

Table 12 summarizes some of the information obtainable from the following equation,

$$\hat{P}(S_x|S) = \frac{P(S_{x+1})}{P(S)} . \tag{7}$$

This equation is used to estimate the conditional probability of observing a sequence of x hours of a weather category. It can be used to answer questions such as: given that the visibility is GE 10 miles, how many hours will it be before there is a 50% probability that the sequence of GE 10 visibilities will be broken. The unconditional probability P(S) is assumed to be known and $\hat{P}(S_x|S)$ must equal 0.50. Substituting, for example, the winter unconditional probability of observing GE 10 miles, 0.5397, into Eq. (7), it becomes

$$P(S_{x+1}) = (0.50)(0.5397) = 0.2699 . \tag{7a}$$

Solutions to Eq. (6) for $\hat{P}(S_{x+1})$ for GE 10 are shown in Figure 3. It can be seen that $\hat{P}(S_{x+1}) = 0.2699$ when $x+1 \approx 15$ hours, therefore, GE 10 is expected to persist for more than 14 hours about 50% of the time. The dots in Figure 3 show values of $RF(S_x)$, for winter. It can be seen that $RF(S_x) = 0.2699$ when $x = 15$ hours. At this point the model and the data are in good agreement.

Table 12 shows that from Eq. (7), when GE 10 is observed in winter, it is expected to persist 14, 29, 49, 65, >72, and >72 hours; 50%, 25%, 10%, 5%, 1%, and 0.1% of the time, respectively. Corresponding observed values are shown in parentheses.

The following equation can be used to estimate how long a sequence of successes is expected to persist, given that the sequence has just begun

$$\hat{P}(S_x|FS) = \frac{P(FS_{x+1})}{P(FS)} . \tag{8}$$

The F preceding the S denotes a failure followed by a success.

Table 11. The Minimum Number of Hours that Each Visibility Category Was Estimated to Persist, at Selected Probability Levels (see text). Observed values are shown in parentheses

Category	Season	Climatic Probability	Probability (Percent)							
			5	25	10	5	1	0.1	13-Yr Maximum	Station With Maximum
GE 10 miles	W	.5397	2(2)	17(18)	37(41)	52(58)	>72(>72)	>72(>72)	211	RDU
	S	.4764	0(0)	10(10)	25(26)	36(41)	61(>72)	>72(>72)	224	RDU
GE 5 miles	W	.7917	20(21)	51(52)	>72(>72)	>72(>72)	>72(>72)	>72(>72)	379*	RDU
	S	.8634	22(22)	49(60)	>72(>72)	>72(>72)	>72(>72)	>72(>72)	399*	BAL
LE 3 miles	W	.1532	0(0)	0(0)	4(5)	10(10)	26(26)	48(53)	75	PHL
	S	.08720	0(0)	0(0)	0(0)	3(3)	11(12)	25(27)	61	JFK
LE 0.25 miles	W	.01460	0(0)	0(0)	0(0)	0(0)	2(2)	11(11)	25	BAL
LE 1 mile	S	.01651	0(0)	0(0)	0(0)	0(0)	2(2)	7(7)	16	EWR

*These values may exceed those shown since the computer program terminated at 400.

Table 12. The Minimum Number of Hours That Each Visibility Category Was Observed to Persist, Given That the Category is Observed, at Selected Probability Levels (see text). Observed values are shown in parentheses

Category	Season	Climatic Probability	Probability (Percent)					
			50	25	10	5	1	0.1
GE 10 miles	W	.5397	14(15)	29(33)	49(56)	65(>72)	>72(>72)	>72(>72)
	S	.4764	10(10)	21(21)	36(41)	47(53)	>72(>72)	>72(>72)
GE 5 miles	W	.7917	29(31)	60(60)	>72(>72)	>72(>72)	>72(>72)	>72(>72)
	S	.8634	26(29)	53(67)	>72(>72)	>72(>72)	>72(>72)	>72(>72)
LE 3 miles	W	.1532	5(6)	11(11)	20(19)	27(29)	43(48)	66(61)
	S	.08720	3(3)	6(6)	11(12)	15(16)	25(28)	39(41)
LE 0.25 miles	W	.01460	2(2)	5(5)	8(8)	11(11)	17(14)	26(*)
LE 1 mile	S	.01651	1(1)	3(3)	5(5)	6(6)	10(9)	15(*)

*No data.

Equation (8) always yields smaller values than Eq. (7), unless the process is first-order Markov in which case the values are identical. A table of values based on solutions to Eq. (8) was not prepared, but sufficient information is included in this report to prepare such a table.

5. RUNS

5.1 Observed

Another way of examining persistence is to consider the number of runs of exactly x hours in length, that is, $n(FS_1F)$, $n(FS_2F), \ldots, n(FS_xF)$. The relative frequency of runs is given by the expression:

$$RF(FS_xF) = \frac{n(FS_xF)}{N-13(x-1)} \approx \frac{n(FS_xF)}{N} \tag{9}$$

where $n(FS_xF)$ is the observed number of runs of exactly x hours in length and N is the total number of hours in the data sample.

The observed number of runs, based on 28,080 hours of winter observations, and 28,704 hours of summer observations, at each of the nine stations is given, for selected hours, in Tables 13 to 16. The median values are indicated with asterisks. Although the frequencies are based on more than 28,000 observations at each station and season, there are large sampling variations. Some examples found in Table 13, in winter, are: LGA had only 48 runs of 3 hours of GE 10 while the nearby station JFK had 80; PHL had only 2 runs of 24 hours but 5 runs of 30 hours; and RIC had 17 runs of 5 hours but 32 runs of 6 hours.

To model the runs it is assumed that one good model can estimate runs at any of the nine stations, at least as well as a 13-year data sample.

A model was considered that is very similar to Eq. (6). This model requires estimates of the conditional probabilities, $\hat{P}(S|FS_x)$. Relative frequencies of success given a failure and x hours of successes were determined from the data with the following expression:

$$RF(S|FS_x) = \frac{n(FS_{x+1})}{n(FS_x)} . \tag{10}$$

These relative frequencies, a selection of which are given in Tables 17 to 20, were used to obtain the required conditional probabilities.

Table 13. Observed Number of Runs, $\hat{n}(FS_xF)$ of x Hours in Length Observed in the Data Sample and Estimated Through the Use of Eq. (11) When GE 10 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	Run Length (hours)											13 Year Maximum
		1	2	3	4	5	6	12	18	24	30	36	
Winter	LGA	113	94	48	54	36	33	24	13	3	1	3	94
	JFK	183	110	80	62	37*	36*	29	16	6	5*	6	105
	EWR	134	91	73	58	42	45	20*	14*	8	9	7	194
	PHL	118	89	50	61	50	47	29	10	2	5*	2	177
	BAL	95	73	67	41	37*	22	16	13	8	6	3*	187
	ADW	101*	64	52*	44*	31	38	18	12	7*	2	2	141
	DCA	100	76*	58	37	40	37	13	16	8	6	7	157
	RIC	62	58	37	24	17	32	22	19	5	3	3*	146
	RDU	87	68	51	36	26	28	19	21	8	4	3*	211
	Median	101	76	52	44	37	36	20	14	7	5	3	
	$\hat{n}(FS_xF)$	108	76	54	44	36	31	17	13	10	8	6	
Summer	LGA	177	110	78	65	57*	51	16	13	6*	4	2	100
	JFK	236	139	89	66*	56	38	20	19	11	8	4	114
	EWR	206	138	105	89	63	46	26	29	4	1	5	101
	PHL	202	135	101	81	71	47*	28*	23	3	0	1	111
	BAL	130	126	92	79	53	53	24	26	7	5*	3*	154
	ADW	144	98	84*	85	60	53	28*	29	8	2	1	141
	DCA	150	94	81	62	55	48	32	25*	9	9	3*	188
	RIC	83	87	81	59	47	43	38	20	5	6	3*	131
	RDU	157*	116*	71	63	57*	40	32	42	6*	7	4	224
	Median	157	116	84	66	57	47	28	25	6	5	3	
	$\hat{n}(FS_xF)$	159	115	91	74	61	52	26	17	12	8	6	

Table 14. Observed Number of Runs, $\hat{n}(FS_xF)$, of x Hours in Length Observed in the Data Sample and Estimated Through the Use of Eq. (11) When GE 5 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	Run Length (hours)											13 Year Maximum
		1	2	3	4	5	6	12	18	24	30	36	
Winter	LGA	160	95	56	43	30	27	14	12	6	6*	11	204
	JFK	171	90	45	40	26	28	9	14	10	7	6	243
	EWR	141	92	55	42	34	35	12	4	5*	7	12	213
	PHL	146	78	63	32	27	20*	24	13	8	4	3	219
	BAL	79	65*	41*	24*	20	28	6	2	7	8	5	296
	ADW	70	42	32	22	11	15	10	2	4	7	2	313
	DCA	111*	55	37	24*	25*	20*	13	8	5*	5	4*	289
	RIC	56	37	26	23	16	13	11*	10	4	1	3	312
	RDU	76	43	22	14	18	12	6	9*	1	0	2	379**
	Median	111	65	41	24	25	20	11	9	5	6	4	
	$\hat{n}(FS_xF)$	115	65	40	29	22	[illegible]	9	8	7	6	5	
Summer	LGA	161	99	71	40	36	31	22*	25	6*	5	5	176
	JFK	167	98	62	63	36	48	27	17	11	3	7	211
	EWR	157	82	59	56	42	30	23	33	12	5	3	241
	PHL	174	118	72	47	46	33	28	36	6*	5	1	165
	BAL	73*	50	31	30	25	23	15	18	5	2	4*	399**
	ADW	70	71*	43*	22	27*	24*	23	13	4	1	4*	312
	DCA	66	35	29	24	15	16	13	23	9	1	3	393**
	RIC	57	42	35	33*	24	18	13	19	6*	4*	2	357
	RDU	70	52	22	19	16	10	8	22*	10	4*	4*	271
	Median	73	71	43	33	27	24	22	22	6	4	4	
	$\hat{n}(FS_xF)$	84	58	43	33	27	23	12	9	8	7	6	

**These values might exceed those shown because the computer program terminated at 400.

Table 15. Observed Number of Runs, $\hat{n}(FS_xF)$, of x Hours in Length Observed in the Data Sample and Estimated Through the Use of Eq. (11) When LE 3 Miles Visibility is Considered a Success. *Median values are identified with asterisks*

Season	Station	Run Length (hours)											13 Year Maximum
		1	2	3	4	5	6	12	18	24	30	36	
Winter	LGA	233	146	88	72	53	35	12	12	3	0	1*	60
	JFK	221	127	89	66	38*	36	13	6	2*	0	1*	53
	EWR	195	128	76	60	48	45	18	9	6	3	3	65
	PHL	202	107*	76	52*	54	27	8	10	2*	2	2	75
	BAL	127	80	52	25	28	32*	10	8*	3	1	0	71
	ADW	94	58	36	30	30	32*	8	9	5	1	3	69
	DCA	171*	110	68*	61	52	42	14	8*	0	0	0	56
	RIC	93	65	55	42	33	29	11*	4	2*	0	1*	67
	RDU	119	74	44	36	26	25	9	3	2*	0	0	40
	Median	171	107	68	52	38	32	11	8	2	0	1	
	$\hat{n}(FS_xF)$	170	107	67	51	41	34	13	7	4	2	1	
Summer	LGA	269	148	85	83	68	44	10	2	1	1	0	56
	JFK	273	147	89	86	48	39	9*	5	1	1	0	61
	EWR	259	160	112	85	63	54	17	1*	1	0	0	40
	PHL	300	173	116	98	69	74	12	3	0	0	0	35
	BAL	158	89	82*	43	47*	27	10	1*	0	0	0	57
	ADW	228*	99	74	40	38	32	6	1*	1	0	0	42
	DCA	187	78	51	49*	28	20	5	1*	0	1	0	43
	RIC	170	97	73	43	38	35*	6	0	0	1	0	56
	RDU	217	117*	75	43	29	16	1	2	0	0	0	28
	Median	228	117	82	49	47	35	9	1	0	0	0	
	$\hat{n}(FS_xF)$	186	110	76	55	40	30	7	2	1	0	0	

Table 16. Observed Number of Runs, $\hat{n}(FS_xF)$, of x Hours in Length Observed in the Data Sample and Estimated Through the Use of Eq. (11) When LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer is Considered a Success. Median values are identified with asterisks

		Run Length (hours)											
Season	Station	1	2	3	4	5	6	12	18	24	30	36	13 Year Maximum
Winter	LGA	21	15	8	3	3	2	0	0	0	0	0	16
	JFK	59	31	16	12*	2	3	0	0	0	0	0	17
	EWR	49*	25*	10	10	5*	1	1*	0	0	0	0	16
	PHL	51	16	14	13	7	10	0	2	0	0	0	18
	BAL	66	31	17	15	9	8	4	0	0	0	0	25
	ADW	66	43	19	16	14	14	4	0	0	0	0	17
	DCA	46	24	15*	4	6	1	1*	0	0	0	0	14
	RIC	29	22	12	11	5*	6*	0	0	0	0	0	15
	RDU	39	30	23	14	1	7	1*	0	0	0	0	15
	Median	49	25	15	12	5	6	1	0	0	0	0	
	$\hat{n}(FS_xF)$	47	25	15	11	8	6	1	0	0	0	0	
Summer	LGA	68	21	22*	10	5	4	0	0	0	0	0	10
	JFK	85*	40	28	14	15	10	2	0	0	0	0	15
	EWR	104	50	19	23	9	8*	1	0	0	0	0	16
	PHL	97	33	20	20	11	8*	0	0	0	0	0	13
	BAL	68	35	22*	10	11	7	0	0	0	0	0	9
	ADW	81	39*	15	15*	6	12	0	0	0	0	0	15
	DCA	23	6	5	1	0	0	0	0	0	0	0	4
	RIC	96	39*	27	21	11	11	1	0	0	0	0	12
	RDU	111	55	30	16	10*	8*	0	0	0	0	0	10
	Median	85	39	22	15	10	8	0	0	0	0	0	
	$\hat{n}(FS_xF)$	91	44	24	14	9	5	0	0	0	0	0	

Table 17. Relative Frequency of Success Given a Failure and x Hours of Success, $RF(S|FS_x)$, Obtained From the Data Sample When GE 10 Miles Visibility is Considered a Success. Median values are identified with asterisks

			x (Hours)																		
Season	Station	p(F)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.5712	.0554	.873*	.879	.930	.915	.938*	.939*	.918	.946*	.957	.953	.950	.938	.930	.922	.951	.939	.938	.950*
	JFK	.5020	.0767	.831	.878	.898	.912	.943	.941	.928	.923	.943	.931	.937	.928	.952*	.958	.950*	.929	.920	.942
	EWR	.4964	.0669	.856	.886	.897	.908	.927	.916	.910	.930	.949*	.962	.939	.944	.952*	.959	.967	.983	.976	.951
	PHL	.5271	.0603	.868	.885	.927	.904	.913	.910	.946*	.935	.938	.940	.944*	.918	.929	.947	.940	.966	.969	.960
	BAL	.4419	.0655*	.883	.898*	.896	.929	.931	.956	.958	.948	.940	.973	.942	.957	.936	.976	.954	.955*	.966	.955
	ADW	.4603*	.0620	.874	.909	.918*	.925*	.943	.925	.947	.951	.955	.953	.964	.952	.955	.929	.936	.956	.947	.955
	DCA	.3976	.0777	.885	.901	.916	.942	.933	.934	.946*	.941	.931	.958	.966	.967	.953	.956*	.969	.950	.960*	.948
	RIC	.4345	.0648	.722	.920	.945	.962	.972	.946	.939	.951	.956	.954*	.943	.949*	.963	.952	.939	.938	.942	.939
	RDU	.2792	.105	.894	.908	.924	.942	.955	.950	.968	.961	.965	.956	.971	.957	.957	.958	.940	.959	.966	.938
Summer	LGA	.6019	.0574	.821	.865	.889	.896	.898	.899	.914	.915	.937	.930	.915	.947	.934	.918	.910	.906	.926	.930
	JFK	.5236*	.0762*	.794	.847	.884	.903	.909	.932	.916	.952	.932	.943	.930*	.946	.935	.939	.922*	.933	.940	.924
	EWR	.5503	.0777	.832	.865	.881	.886	.908	.926*	.928	.900	.926*	.922	.920	.932	.915	.907	.928	.912*	.876	.867
	PHL	.6271	.0640	.825	.858	.876	.887	.888	.916	.891	.920	.912	.899	.911	.911	.878	.881	.919	.912*	.893	.862
	BAL	.4757	.0833	.886	.875*	.896*	.900*	.025	.919	.934	.906	.932	.933*	.930*	.942	.946	.910	.908	.931	.937	.902*
	ADW	.5141	.0758	.871*	.899	.904	.893	.915*	.918	.939	.923*	.922	.930	.918	.931	.921	.934	.926	.907	.912	.884
	DCA	.3767	.112	.876	.911	.916	.930	.933	.938	.924*	.932	.923	.937	.944	.937*	.933	.946	.936	.944	.932	.928
	RIC	.5256	.0658	.916	.904	.902	.920	.931	.932	.926	.962	.926*	.939	.950	.913	.914	.934	.915	.897	.910	.921
	RDU	.3321	.138	.881	.900	.932	.935	.937	.953	.924*	.927	.945	.953	.947	.946	.930*	.927*	.930	.920	.913*	.889

Table 18. Relative Frequency of Success Given a Failure and x Hours of Success, $RF(S|FS_x)$, Obtained From the Data Sample When GE 5 Miles Visibility is Considered a Success. Median values are identified with asterisks

			x (hours)																		
Season	Station	p(F)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.2490	.137	.833	.881	.920	.934	.950	.953	.963*	.972*	.957	.961	.970	.969	.946	.952	.977	.967*	.973	.967
	JFK	.2083*	.156	.813	.879	.931	.934	.954*	.948	.946	.965	.968	.987	.962	.979	.976	.968	.965	.979	.963	.961
	EWR	.2567	.128*	.847*	.882	.920	.934	.942	.937	.954	.932	.959	.968	.965	.971	.958	.966*	.984	.967*	.975	.988
	PHL	.2528	.127	.838	.897*	.907	.948*	.954*	.964	.974	.948	.966	.956	.978	.946	.969	.951	.967	.955	.978	.963
	BAL	.2118	.115	.884	.892	.924	.952	.958	.938	.953	.978	.970*	.982	.966	.984	.969	.962	.970	.960	.977	.993
	ADW	.1786	.112	.875	.914	.929*	.947	.972	.961	.981	.983	.983	.971*	.979	.970*	.978	.972	.980	.967*	.972*	.993
	DCA	.1912	.138	.851	.913	.936	.956	.952	.959*	.960	.951	.972	.966	.953	.966	.976	.962	.980	.971	.970	.975
	RIC	.1646	.126	.904	.930	.947	.951	.964	.970	.976	.980	.972	.974	.979	.970*	.972	.991	.962	.976	.969	.968*
	RDU	.1214	.146	.847*	.898	.942	.961	.948	.963	.974	.977	.970*	.972	.968*	.978	.970*	.988	.976*	.980	.955	.961
Summer	LGA	.2168	.178	.855	.895	.916	.948*	.951	.956	.946	.945	.936	.952	.964	.957	.968*	.960	.965*	.955	.931	.936
	JFK	.2018	.192	.850	.896	.927	.920	.950	.930	.967	.940	.945	.960	.954	.946	.964	.961	.948	.954	.947	.955
	EWR	.2128	.185	.861	.916*	.934*	.933	.946	.959*	.959*	.948	.964	.950	.966*	.960*	.967	.968	.951	.961	.940	.925
	PHL	.2321	.186	.859	.889	.924	.946	.944	.958	.952	.952	.954	.961*	.952	.952	.948	.961	.949	.934	.916	.913
	BAL	.1366*	.199*	.906	.929	.953	.952	.958	.960	.971	.970	.959	.970	.971	.968	.982	.964*	.963	.973	.940	.952
	ADW	.1296	.214	.912	.902	.934*	.964	.954*	.958	.956	.954*	.961*	.956	.965	.947	.973	.955	.974	.957*	.972	.963
	DCA	.0783	.271	.892*	.936	.943	.950	.967	.964	.967	.973	.972	.974	.987	.965	.981	.974	.983	.959	.969	.927
	RIC	.1279	.204	.924	.939	.946	.946	.959	.968	.957	.975	.972	.969	.966*	.972	.957	.984	.967	.960	.941*	.948
	RDU	.0883	.283	.902	.920	.963	.967	.971	.981	.977	.965	.966	.975	.981	.983	.982	.991	.968	.951	.951	.943*

Table 19. Relative Frequency of Success Given a Failure and x Hours of Success, RF(S|FS_x), Obtained From the Data Sample When LE 3 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	p(F)	x (hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.8158	.0387	.737	.776	.826	.828	.847	.881	.853	.887	.847	.855	.866	.902	.874*	.845	.902	.838	.903	.786
	JFK	.8468*	.0329	.718	.774	.795	.809	.864*	.851	.859	.847	.867	.854	.856	.863	.890	.932	.897*	.951	.845	.878*
	EWR	.7987	.0370	.765	.798*	.850	.861	.871	.861	.874	.876*	.906	.870*	.845	.873	.903	.911*	.902	.880	.901*	.877
	PHL	.8034	.0351	.745	.819	.843	.872	.848	.910	.905	.843	.900	.856	.901	.945	.869	.899	.897*	.885	.953	.876
	BAL	.8323	.0248	.781	.824	.861	.922	.906	.881	.899	.892	.874	.904	.907	.926	.833	.952	.900	.900	.889	.889
	ADW	.8501	.0204	.806	.852	.892	.899	.888	.866*	.893	.897	.921	.868	.886*	.932	.972	.887	.936	.898*	.949	.880
	DCA	.8488	.0295*	.757*	.793	.839	.828	.822	.826	.874	.862	.893	.888	.908	.870	.872	.927	.882	.925	.806	.840
	RIC	.8675	.0207	.815	.842	.841*	.856*	.867	.866*	.877*	.915	.853	.875	.848	.884*	.810	.956	.846	.945	.904	.915
	RDU	.9024	.0182	.742	.784	.836	.839	.862	.846	.898	.846	.885*	.870*	.888	.873	.919	.877	.860	.767	.879	.896
Summer	LGA	.8631	.0357	.696*	.760	.818	.783	.773	.810	.798	.787	.873	.796	.744	.810*	.863	.864	.842	.625	.900	.889*
	JFK	.8645	.0353	.689	.757*	.805	.766	.830	.833	.790*	.760	.795	.849	.835	.864	.895	.784	.825	.818*	.852*	.783
	EWR	.8541	.0382	.724	.764	.784	.791	.804	.791*	.794	.790	.820	.838	.784	.754	.865*	.756	.765	.808	.952	.950
	PHL	.8414	.0435	.714	.769	.799	.787*	.810	.748	.795	.788*	.739	.755	.831	.812	.731	.842*	.812*	.923	.792	.842
	BAL	.9128*	.0213	.717	.778	.737	.813	.749	.807	.832	.808	.789	.800*	.812	.744	.896	.885	.696	.812	.923	.917
	ADW	.9154	.0234*	.630	.745	.744	.814	.783*	.766	.781	.768	.873	.945	.769	.850	.824	.857	.833	.900	.722	.923
	DCA	.9522	.0164	.582	.701	.721	.629	.663	.636	.714	.800	.950	.842	.875	.643	1.00	.556	1.00	.800	1.00	.750
	RIC	.9189	.0213	.698	.752	.752*	.806	.788	.752	.726	.792	.770	.766	.806*	.793	.913	.714	.800	.833	.700	1.00
	RDU	.9400	.0207	.612	.658	.667	.713	.729	.795	.694	.721	.806*	.800*	.750	.933	.714	1.00	.700	.857	.833	.600

Table 20. Relative Frequency of Success Given a Failure and x Hours of Success, RF(S|FS_x), Obtained From the Data Sample When LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer is Considered a Success. Median values are identified with asterisks

Season	Station	p(F)	x (hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	LGA	.9921	.00222	.661	.634	.692	.833	.800	.833	.700*	.857*	.667*	1	1	1	.750*	1	.667*	0	0	0
	JFK	.9837	.00521	.590	.635	.704	.684	.923	.875	.762	.938	.600	.667	.833*	1	.600	1	.667*	.500	0	0
	EWR	.9871	.00415	.574	.621	.756*	.677	.762	.938	.867	.923	.667*	.875	.714	.800*	.750*	1	.667*	0	0	0
	PHL	.9809	.00497	.628	.814	.800	.768*	.837	.722	.769	.750	.800	.750	.667	1	.833	.800*	.500	1	1	0
	BAL	.9736	.00669	.639*	.735	.802	.783	.833	.822*	.784	.828	.833	.950	.737	.714	.800	.750	.833	.800	.500	1
	ADW	.9730	.00750	.678	.691	.802	.792	.770	.702	.636	.857*	.833	.933*	.928	.692	.444	.750	.333	1	0	0
	DCA	.9906	.00374	.558	.586	.559	.789	.600	.889	.625	.600	.667*	1	1	.500	1	0	0	0	0	0
	RIC	.9870	.00368	.716	.699	.765	.718	.821*	.739	.470	.750	.667*	1	.750	1	.667	.500	0	0	0	0
	RDU	.9854*	.00466*	.698	.667*	.617	.622	.956	.682	.600	1	.667*	.500	1	.667	.500	1	0	0	0	0
Summer	LGA	.9888	.00483	.504	.696	.542	.615	.688	.636	.571	.250	1	0	0	0	0	0	0			
	JFK	.9786	.00755	.599	.685	.678	.763	.667*	.667	.600*	.583	.714	.800	.750	.333	1	1	0			
	EWR	.9806	.00796	.536	.583	.728	.549	.678	.579	.727	1	.750	.500*	1	.667	1	1	.500			
	PHL	.9835*	.00698*	.508	.670	.701	.574	.592	.500	.500	.500*	1	1	.500*	1	0	0	0			
	BAL	.9865	.00562	.572	.615*	.607	.706	.542	.462	.500	.333	0	0	0	0	0	0	0			
	ADW	.9844	.00626	.542	.594	.737	.643	.778	.428	.667	.500*	.667*	1	1	1	.500	0	0			
	DCA	.9981	.00122	.343	.500	.167	0	0	0	0	0	0	0	0	0	0	0	0			
	RIC	.9802	.00775	.560	.680	.675*	.625*	.686	.542*	.692	.333	.667*	.500*	1	0	0	0	0			
	RDU	.9803	.00856	.539*	.577	.600	.644	.655	.579	.636	.714	.600	0	0	0	0	0	0			

5.2 Modeled

The probability of a run of exactly x hours in length, $P(FS_xF)$, is the probability that there will be a failure followed by x successes followed by another failure. This might be estimated as follows, for runs of length 1, 2, and x hours, respectively:

$$\left.\begin{aligned} \hat{P}'(FS_xF) &= \hat{P}(F)\ \hat{P}(S|F)\ \hat{P}(F|FS_x) && x=1 \\ \hat{P}'(FS_xF) &= \hat{P}(F)\ \hat{P}(S|F)\ \hat{P}(S|FS_{x-1})\ \hat{P}(F|FS_x) && x=2 \\ \hat{P}'(FS_xF) &= \hat{P}(F)\ \hat{P}(S|F)\ \hat{P}(S|FS_1)\ \hat{P}(S|FS_2)\ldots\hat{P}(S|FS_{x-1})\ \hat{P}(F|FS_x) && x\geq 3 \end{aligned}\right\}\quad (11)$$

where $\hat{P}(S|F)$ is the estimated probability of a success given that a failure occurred the previous hour, $\hat{P}(S|FS_1)$ is the estimated probability of a success given that a success occurred and a failure occurred 2 hours earlier, ..., $\hat{P}(F|FS_x)$ is the estimated probability of a failure given that x successes occurred the previous x consecutive hours and a failure occurred x+1 hours earlier. The unconditional and conditional probabilities can be estimated from the relative frequencies but very large samples of data are required to obtain statistically stable relative frequencies of long runs, because they are rare events.

The points plotted in Figure 7 show the nine-station median relative frequencies of success given a failure and x hours of successes have occurred. The median values are given in Table 21. Smooth curves were subjectively drawn through the points in Figure 7. The probabilities required for the solution of Eq. (11) were estimated from these curves.

Table 21 shows values of $\hat{P}(S|FS_x)$ that were estimated from the curves shown in Figure 7. The conditional probabilities always increase for at least 8 hours and most of the values increase for at least 12 hours.

Table 21. Median Values of $RF(S|FS_x)$ Obtained From the Data Sample (Tables 17, 18, 19, and 20) and Probability Estimates $\hat{P}(S|FS_x)$ Determined From Subjectively Drawn Curves of the Medians Shown in Figure 7

			x (hours)																		
Season		p(F)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Winter	GE 10 miles																				
	Median	.4603	.0655	.873	.898	.918	.925	.938	.939	.946	.946	.949	.954	.944	.949	.952	.956	.950	.955	.960	.950
	$\hat{P}(S\|FS_x)$			.873	.897	.918	.928	.937	.941	.944	.947	.951	.953	.954	.955	.955	.955	.955	.955	.955	.955
	GE 5 miles																				
	Median	.2083	.128	.847	.897	.929	.948	.954	.959	.963	.972	.970	.971	.968	.970	.970	.966	.976	.967	.972	.968
	$\hat{P}(S\|FS_x)$			.847	.897	.929	.945	.955	.962	.965	.969	.973	.974	.976	.977	.978	.978	.978	.978	.978	.978
	LE 3 miles																				
	Median	.8468	.0295	.757	.798	.841	.856	.864	.866	.877	.876	.885	.870	.886	.884	.874	.911	.897	.898	.901	.878
	$\hat{P}(S\|FS_x)$			.757	.798	.841	.856	.866	.871	.878	.882	.887	.891	.895	.898	.900	.902	.903	.904	.904	.904
	LE 0.25 miles																				
	Median	.9854	.00466	.639	.667	.756	.768	.821	.822	.700	.857	.667	.933	.833	.800	.750	.800	.667	0	0	0
	$\hat{P}(S\|FS_x)$			.639	.700	.738	.750	.758	.762	.766	.768	.770	.771	.772	.772	.772	.772	.772	.772	.772	.772
Summer	GE 10 miles																				
	Median	.5236	.0762	.871	.875	.896	.900	.915	.926	.924	.923	.926	.933	.930	.937	.930	.927	.922	.912	.913	.902
	$\hat{P}(S\|FS_x)$			.861	.883	.896	.905	.913	.920	.926	.930	.932	.933	.935	.937	.938	.939	.939	.939	.939	.939
	GE 5 miles																				
	Median	.1366	.199	.892	.916	.934	.948	.954	.959	.959	.954	.961	.961	.966	.960	.968	.964	.965	.957	.941	.943
	$\hat{P}(S\|FS_x)$			.892	.916	.932	.945	.952	.957	.962	.964	.967	.969	.970	.972	.973	.974	.975	.975	.975	.975
	LE 3 miles																				
	Median	.9128	.0234	.696	.757	.752	.787	.783	.791	.790	.788	.806	.800	.806	.810	.865	.842	.812	.818	.852	.889
	$\hat{P}(S\|FS_x)$			.696	.742	.760	.773	.785	.793	.800	.807	.813	.819	.825	.831	.836	.839	.843	.847	.849	.850
	LE 1 mile																				
	Median	.9835	.00698	.539	.615	.675	.625	.667	.542	.600	.500	.667	.500	.500	0	0	0	0	0	0	0
	$\hat{P}(S\|FS_x)$			.539	.585	.608	.624	.633	.637	.639	.640	.640	.640	.640	.640	.640	.640	.640	.640	.640	.640

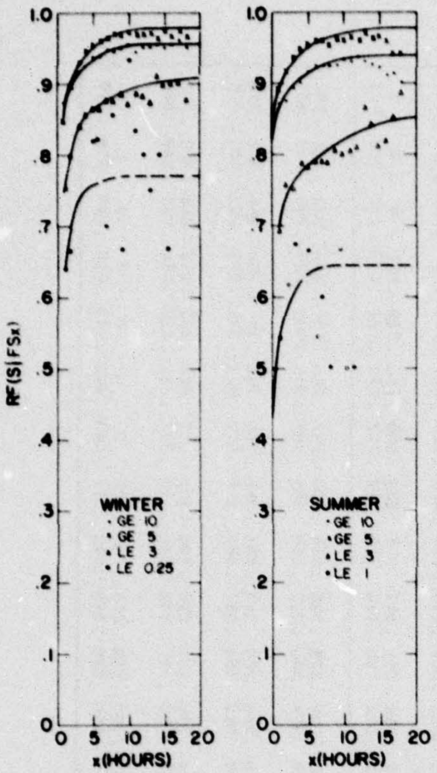

Figure 7. Relative Frequencies of Success Given Exactly x Hours of Consecutive Success Have Occurred, in Winter (a) and Summer (b). The curves were subjectively drawn. The dashed portions of the curves are based on fewer than 30 cases

The values found in Table 21 were used to solve Eq. (11). By substituting $\hat{P}'(FS_xF)$ from Eq. (11) for $RF(FS_xF)$ in Eq. (9) the following expression is obtained for estimating $n(FS_xF)$

$$\hat{n}(FS_xF) = \hat{P}'(FS_xF)N \; . \qquad (12)$$

Solutions to Eq. (12) are given in Tables 13 to 16. The agreements between the observed number of runs and those calculated from Eq. (12) are very good. It should be understood that this is not an independent test of Eq. (12) but rather a subjective fitting to the data to obtain conditional probabilities and an objective method for finding the desired probability estimates.

6. RECURRENCE

6.1 Observed

The relative frequency of the recurrence of a success ℓ hours later given that a success occurred, $RF(S_\ell | S)$, can be determined from the data by dividing the number of occurrences of successes spaced ℓ hours apart, $n(SS_\ell)$, by the total number of successes, $n(S)$, that is,

$$RF(S_\ell | S) = \frac{n(SS_\ell)}{n(S)} . \tag{13}$$

Conditional recurrence relative frequencies based on 13 years of hourly observations taken at each of the nine stations are given, for selected hours, in Tables 22 to 25. The median values for each season are also given in the tables and plotted in Figures 8 to 11. The curves for summer show a pronounced 24-hourly period.

6.2 Modeled

McAllister[6] proposed an expression of the form

$$\hat{P}(S_{t+\ell} | S_t) = P(S_{t+\ell}) + [1-P(S_t)] e^{-a\ell^b} \tag{14}$$

for estimating recurrence probabilities of cloud cover. He used $a = 0.263$ and $b = 0.632$ as the best estimates of the parameters. Gringorten[7] showed that Eq. (14) yields probability estimates very close to those obtained from the bivariate normal distributions if the parameter b is fixed at 0.620 and a is allowed to vary with the climatic frequency of the event and the basic persistence of the element.

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6. McAllister, C.R. (1969) Cloud-cover recurrence and diurnal variation, J. Appl. Meteor. 8:769-777.

7. Gringorten, I.I. (1971) Modeling conditional probability, J. Appl. Meteor. 10:646-657.

Table 22. Relative Frequency of the Recurrence of a Success ℓ Hours After a Success Has Occurred, $RF(S_\ell | S)$, Observed in the Data Sample and Estimated Through the Use of Eq. (15) When GE 10 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	p(S)	ℓ(hours) 1	2	3	4	5	6	9	12	18	24	30	36	48	60	71
Winter	LGA	.429	.926	.873	.829	.792	.761	.733	.667	.613	.543	.505	.425	.386	.415	.392	.429
	JFK	.498	.923	.874	.832	.798	.770	.745	.688	.651	.599	.566	.514	.487	.492	.468	.494
	EWR	.504	.934	.890	.855	.825	.800	.777	.725	.679	.610	.561	.505	.475	.487	.471	.499
	PHL	.473	.933	.885	.846	.813	.785	.760	.702	.658	.604	.570	.508	.480	.475	.456	.477
	BAL	.558	.948	.909*	.878	.854	.834	.816	.770	.738	.691	.659*	.611*	.586*	.576*	.557	.573*
	ADW	.540*	.947*	.910	.879	.853	.831	.811	.768	.734	.692	.666	.625	.599	.590	.566	.577
	DCA	.602	.949	.911	.879	.852	.830	.811	.771	.742	.701	.685	.640	.624	.629	.602	.611
	RIC	.565	.950	.909	.876*	.847*	.821*	.799*	.747*	.712*	.676*	.664	.615	.587	.596	.556*	.574
	RDU	.721	.959	.931	.908	.890	.874	.860	.830	.809	.790	.782	.751	.733	.734	.707	.723
	Median	.540	.947	.909	.876	.847	.821	.799	.747	.712	.676	.659	.611	.586	.576	.556	.573
	Eq. (15)		.910	.866	.833	.808	.790	.774	.738	.712	.683	.687	.638	.618	.620	.581	.587
Summer	LGA	.398	.913	.854	.806	.765	.731	.702	.636	.591	.548	.545	.483	.438	.434	.401	.432
	JFK	.476*	.916	.866*	.826	.792	.763	.736	.677	.640*	.616*	.612	.562	.522	.536	.490	.503
	EWR	.450	.905	.840	.788	.746	.711	.682	.614	.581	.569	.594	.514	.466	.507	.440	.495
	PHL	.373	.892	.817	.759	.710	.667	.631	.549	.507	.506	.554	.462	.412	.472	.360	.430
	BAL	.524	.924	.869	.826	.792	.765	.741	.692	.666	.649	.659	.612	.583	.598	.546	.562
	ADW	.486	.920*	.864	.821	.785*	.758*	.734*	.676*	.642	.639	.650	.602	.565	.593	.530	.564
	DCA	.623	.932	.886	.849	.819	.793	.770	.626	.707	.705	.728	.669	.649	.685	.624	.657
	RIC	.474	.927	.869	.822*	.784	.751	.722	.657	.621	.614	.644*	.574*	.529*	.571*	.491*	.545*
	RDU	.668	.931	.884	.848	.818	.794	.775	.738	.720	.725	.775	.706	.682	.740	.669	.726
	Median	.476	.920	.866	.822	.785	.758	.734	.676	.640	.616	.644	.574	.529	.571	.491	.545
	Eq. (15)		.912	.859	.816	.780	.750	.724	.671	.640	.633	.664	.588	.551	.592	.516	.555

Table 23. Relative Frequency of the Recurrence of a Success ℓ Hours After a Success Has Occurred, $RF(S_\ell | S)$, Observed in the Data Sample and Estimated Through the Use of Eq. (15) When GE 5 Miles Visibility is Considered a Success. Median values are identified with asterisks

			ℓ (hours)														
Season	Station	p(S)	1	2	3	4	5	6	9	12	18	24	30	36	48	60	71
Winter	LGA	.751	.954	.926	.905	.888	.874	.862	.833	.809	.784	.776	.755	.744	.752	.740	.747
	JFK	.792*	.959	.936	.919	.904	.892	.881	.857	.838	.816	.809	.797	.789	.791	.785	.788*
	EWR	.743	.956	.928	.907	.890	.876	.863	.832	.808	.781	.770	.750	.738	.743	.731	.741
	PHL	.747	.957	.931	.911	.895	.882	.869	.838	.817	.795	.782	.763	.749	.751	.740	.752
	BAL	.788	.969	.948	.933	.921	.911	.901	.875*	.857*	.834*	.819*	.802*	.796*	.795*	.785*	.786
	ADW	.821	.976	.959	.947	.936	.926	.918	.896	.878	.857	.845	.834	.827	.827	.815	.816
	DCA	.809	.967*	.947*	.930*	.917*	.907*	.897*	.877	.860	.843	.837	.822	.815	.816	.804	.807
	RIC	.835	.975	.957	.943	.931	.921	.912	.892	.878	.863	.858	.846	.842	.843	.832	.834
	RDU	.879	.980	.967	.958	.949	.942	.936	.921	.913	.903	.896	.887	.882	.881	.876	.876
	Median	.792	.967	.947	.930	.917	.907	.897	.875	.857	.834	.819	.802	.796	.795	.785	.788
	Eq. (15)		.956	.933	.916	.903	.893	.886	.869	.857	.843	.842	.826	.819	.818	.807	.809
Summer	LGA	.783	.951	.921	.899	.880	.864	.851	.829	.819	.815	.829	.799	.787	.807	.781	.800
	JFK	.798	.951	.924	.902	.885	.871	.860	.838	.828	.829	.838	.815	.803	.824	.797	.813
	EWR	.787	.950	.921	.898	.878	.864	.852	.831	.821	.817	.838	.803	.793	.817	.785	.808
	PHL	.768	.944	.909	.884	.863	.846	.833	.805	.795	.800	.826	.786	.768	.805	.762	.791
	BAL	.863*	.968*	.948*	.933*	.921*	.913*	.906*	.893*	.886*	.884*	.892*	.872*	.866*	.876*	.861*	.869*
	ADW	.870	.969	.949	.935	.925	.917	.911	.902	.896	.891	.896	.879	.876	.883	.870	.875
	DCA	.922	.977	.964	.955	.949	.945	.941	.935	.931	.930	.935	.926	.922	.926	.919	.921
	RIC	.872	.970	.950	.936	.926	.917	.909	.895	.891	.887	.898	.881	.874	.888	.871	.881
	RDU	.912	.972	.957	.947	.940	.934	.930	.922	.919	.917	.928	.914	.911	.921	.909	.917
	Median	.863	.968	.948	.933	.921	.913	.906	.893	.886	.884	.892	.872	.866	.876	.861	.869
	Eq. (15)		.964	.946	.931	.921	.912	.906	.893	.886	.885	.900	.875	.867	.882	.860	.872

Table 24. Relative Frequency of the Recurrence of a Success ℓ Hours After a Success Has Occurred, $RF(S_\ell | S)$, Observed in the Data Sample and Estimated Through the Use of Eq. (15) When LE 3 Miles Visibility is Considered a Success. Median values are identified with asterisks

Season	Station	p(S)	ℓ (hours)														
			1	2	3	4	5	6	9	12	18	24	30	36	48	60	71
Winter	LGA	.184	.829	.731	.658	.599	.556	.518	.429	.358	.280	.266*	.205	.171	.186*	.158	.172
	JFK	.153*	.818	.721	.650	.591	.545	.502	.405	.336	.252	.216	.176	.154	.153	.138	.156*
	EWR	.201	.853*	.762*	.696	.638	.591	.549	.452	.382	.305	.277	.215*	.182*	.205	.171	.200
	PHL	.197	.856	.769	.702	.646	.599	.557	.459	.394	.330	.303	.239	.203	.220	.184	.225
	BAL	.168	.877	.795	.731	.680	.632	.592	.494	.419	.356	.289	.237	.211	.202	.170	.171
	ADW	.150	.884	.805	.744	.691	.644	.601	.500	.423	.317	.264	.218	.187	.182	.136	.138
	DCA	.151	.834	.735	.663	.599	.551	.515	.434*	.364*	.292*	.280	.220	.185	.190	.144*	.151
	RIC	.132	.864	.768	.694*	.636*	.583*	.536*	.429	.356	.275	.244	.195	.174	.169	.126	.128
	RDU	.0976	.832	.729	.664	.602	.546	.500	.399	.335	.254	.216	.163	.128	.136	.0930	.0974
	Median	.153	.853	.762	.694	.636	.583	.536	.434	.364	.292	.266	.215	.182	.186	.144	.156
	Eq. (15)		.796	.693	.620	.563	.520	.486	.413	.364	.310	.299	.243	.218	.215	.180	.187
Summer	LGA	.137	.775	.646	.553	.473	.410	.365	.294	.264	.248	.304	.182	.154	.216	.136	.202
	JFK	.135	.774	.651	.549	.475	.419	.370	.284	.250	.254	.296	.204	.164	.238	.139	.199
	EWR	.146	.776	.645	.550	.469	.408	.360	.292	.260	.242	.332	.194	.166	.256	.148	.236
	PHL	.159	.769*	.634	.530	.449	.388	.337	.246	.219*	.245	.352	.205	.149	.271	.131	.236
	BAL	.0872*	.777	.630*	.523*	.447*	.384	.341*	.250*	.209	.205*	.254	.142	.102	.173	.0835*	.130
	ADW	.0846	.746	.614	.514	.442	.388*	.346	.277	.242	.205*	.259*	.149*	.118*	.170	.0794	.118
	DCA	.0478	.673	.520	.406	.327	.274	.238	.180	.141	.132	.192	.0934	.0744	.103	.0336	.0737
	RIC	.0811	.759	.610	.501	.421	.352	.300	.215	.177	.167	.250	.129	.0893	.178*	.0794	.143*
	RDU	.0600	.675	.502	.387	.310	.257	.216	.145	.113	.0993	.209	.0627	.0488	.140	.0494	.120
	Median	.0872	.769	.630	.523	.447	.388	.341	.250	.219	.205	.259	.149	.118	.178	.0835	.143
	Eq. (15)		.758	.620	.517	.448	.390	.346	.260	.219	.206	.272	.153	.118	.184	.093	.151

Table 25. Relative Frequency of the Recurrence of a Success ℓ Hours After a Success Has Occurred, RF(S_ℓ|S), Observed in the Data Sample and LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer is Considered a Success. Median values are identified with asterisks

Season	Station	p(S)	ℓ (hours)														
			1	2	3	4	5	6	9	12	18	24	30	36	48	60	71
Winter	LGA	.00787	.719*	.552	.448	.376	.317	.267*	.158	.0995*	.0452*	0	0	0	.00452	0	0
	JFK	.0163	.685	.551*	.449*	.381	.333	.269	.179	.142	.0700	.0569*	.0263	.0153*	.0263*	.0131*	.0197*
	EWR	.0129	.682	.547	.459	.389	.329	.282	.160*	.0967	.0387	.0166	.0110	.0138	.0276	.00276	.0249
	PHL	.0191	.745	.618	.508	.415	.356	.285	.181	.136	.102	.0838	.0484	.0261	.0130	0	.00559
	BAL	.0264	.753	.623	.534	.443	.381	.331	.205	.138	.138	.131	.0742	.0378	.0526	.0270	.0108
	ADW	.0270	.729	.568	.464	.379*	.317*	.255	.186	.129	.0938	.115	.0700	.0436	.0726	.0502	.0502
	DCA	.00937	.604	.430	.327	.247	.201	.160	.0684	.0342	.0330	.0570	.0152*	.00760	.0152	.0152	0
	RIC	.0130	.720	.536	.412	.313	.247	.187	.118	.0687	.0357	.0302	.00824	.0110	.0357	.0385	.0330
	RDU	.0146*	.685	.493	.385	.307	.254	.188	.0829	.0390	.0269	.0195	.00244	.0171	.0219	.00732	.0317
	Median	.0146	.719	.551	.449	.379	.317	.267	.160	.0995	.0452	.0569	.0152	.0153	.0263	.0131	.0197
	Eq. (15)		.630	.490	.386	.311	.258	.216	.138	.0995	.0726	.0685	.0379	.0257	.0291	.0162	.0215
Summer	LGA	.0111	.572	.394	.262*	.191	.141	.106	.0469	.0437	.0375	.0375	.0187*	.0156*	.0469	.0250	.0312
	JFK	.0214	.655	.485	.376	.287	.221	.158	.0717	.0521	.0651	.0977	.0603	.0244	.0717	.0163	.0407*
	EWR	.0194	.599	.419	.312	.224	.167	.131	.0753	.0466	.0233	.0735	.0179	.0197	.0609	.0125*	.0591
	PHL	.0165*	.584	.403*	.245	.150	.0949	.0633	.0380	.0316	.00844	.0844*	.0105	.00422	.0633*	.00844	.0422
	BAL	.0135	.589*	.382	.245	.176	.114	.101	.0568	.0284	.0362	.0620	.0258	.0232	.0465	.0103	.0388
	ADW	.0156	.605	.413	.301	.203	.147	.0938*	.0424*	.0312*	.0357	.0132	.0223	.0312	.0670	.0112	.0357
	DCA	.00188	.352	.130	.0185	0	0	0	0	0	0	0	0	0	0	0	0
	RID	.0197	.615	.416	.200	.185*	.120*	.0882	.0388	.0141	.0264	.115	.0335	.0141	.0899	.0159	.0564
	RDU	.0197	.573	.361	.239	.163	.104	.0637	.0177	.0159	.0301*	.134	.0159	.0124	.0761	.0159	.0867
	Median	.0165	.589	.403	.262	.185	.120	.0938	.0424	.0312	.0301	.0844	.0187	.0156	.0633	.0125	.0407
	Eq. (15)		.472	.295	.194	.136	.101	.0775	.0448	.0312	.0237	.0545	.0138	.0099	.0364	.0081	.0317

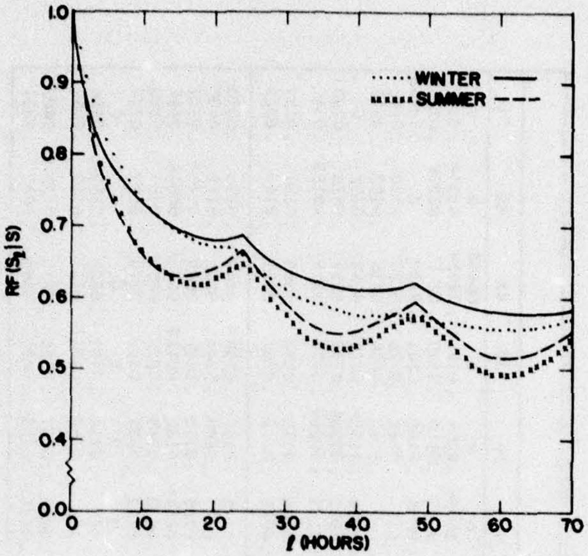

Figure 8. Relative Frequencies of a Success, GE 10 Miles Visibility, ℓ Hours Later Given a Success Has Occurred, in Winter (dots) and in Summer (X's). The solid curve is the solution to Eq. (15) with a' = 0.158 for winter, and the dashed curve is for summer with a' = 0.163

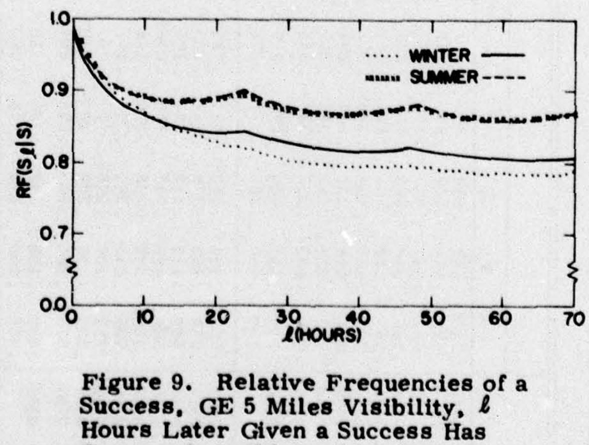

Figure 9. Relative Frequencies of a Success, GE 5 Miles Visibility, ℓ Hours Later Given a Success Has Occurred, in Winter (dots) and in Summer (X's). The solid curve is the solution to Eq. (15) with a' = 0.224 for winter, and the dashed curve is for summer with a' = 0.175

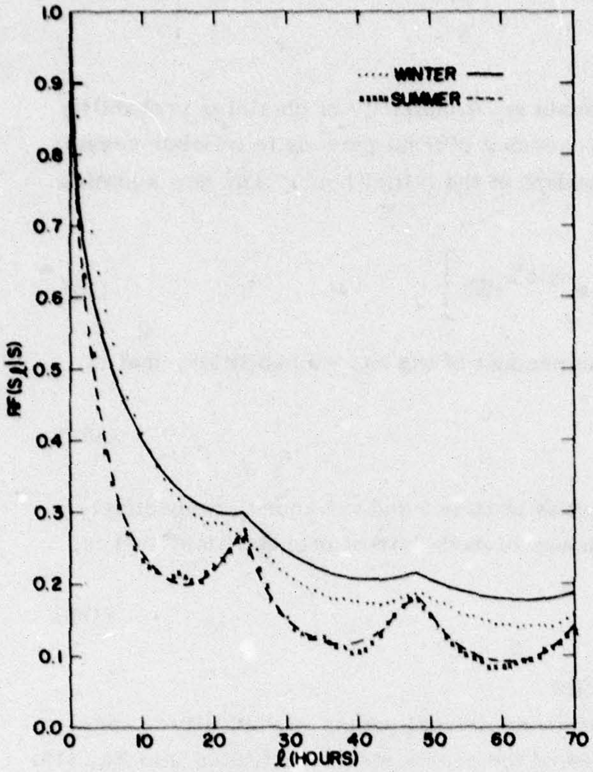

Figure 10. Relative Frequencies of a Success, LE 3 Miles Visibility, ℓ Hours Later Given a Success Has Occurred, in Winter (dots) and in Summer (X's). The solid curve is the solution to Eq. (15) with a' = 0.260 for winter, and the dashed curve is for summer with a' = 0.263

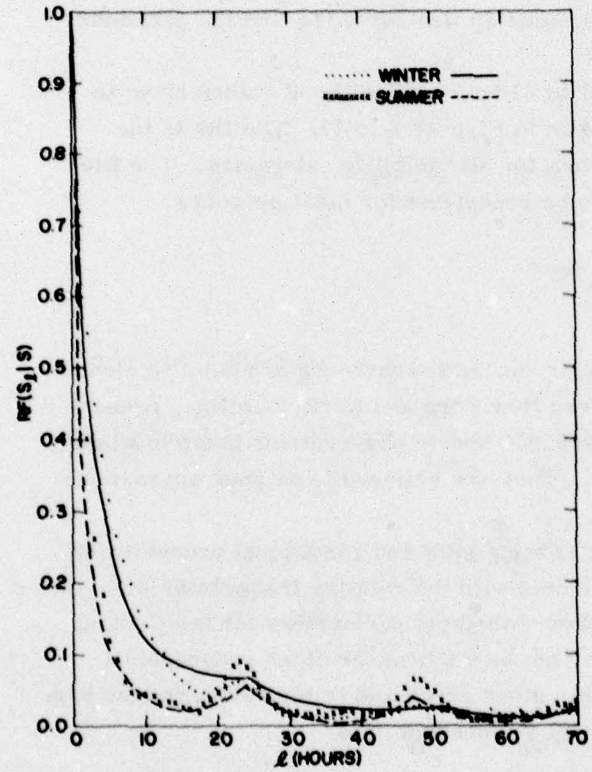

Figure 11. Relative Frequencies of a Success, LE 0.25 Miles Visibility in Winter and LE 1 Mile in Summer, ℓ Hours Later Given a Success Has Occurred, in Winter (dots) and in Summer (X's). The solid curve is the solution to Eq. (15) with a' = 0.425 for winter, and the dashed curve is for summer with a' = 0.524

Eq. (14) was modified to: (1) eliminate any possibility of obtaining probability estimates greater than one; (2) take into account diurnal periods in weather events; and (3) obtain climatic estimates independent of the initial hour. The new equation was expressed as follows:

$$\hat{P}(S_\ell | S) = \frac{1}{P(S)} \left[(1 - e^{-a'\ell^b}) (\overline{YZ}) + e^{-a'\ell^b} (\overline{W}) \right] \tag{15}$$

where $\overline{YZ}$ is the temporal average of the product of the two probabilities, that is,

$$\overline{YZ} = \frac{1}{24} \sum_{t=0}^{23} (Y_t Z_{t+\ell}) \tag{15a}$$

Where Y and Z are probabilities of success at time t and $t+\ell$ hours, respectively; and, $\overline{W}$ is the temporal average of the lower of each pair of probabilities, that is,

$$\overline{W} = \frac{1}{24} \sum_{i=0}^{23} W_i \tag{15b}$$

where $W_i = Y_t$ *or* $Z_{t+\ell}$ *whichever is smaller.*

Table 26 shows that there is a pronounced diurnal period in visibility occurrences. The hourly climatic frequencies of the events were substituted into Eq. (15) using ℓ = 12 hours and b = 0.620 and the equation was solved to find the parameter a'. The a' values are given in Table 27.

Eq. (15) was solved for lags from 1 to 71 hours using the a' values given in Table 27. The resulting curves are shown in Figures 8 to 11. The fits to the summer relative frequencies are excellent for all visibility categories. The fits to the winter values are also believed to be acceptable for most purposes.

7. REMARKS

Relative frequencies of persistence, runs, and recurrence of visibility along the east coast of the United States between New York and North Carolina, presented in this paper, are based on more than 250,000 hourly observations taken in winter and a similar number taken in summer. They are believed to be good approximations of the true probabilities.

Models are presented for use in estimating joint and conditional probabilities. The estimates are usually in good agreement with the relative frequencies when the parameters are carefully chosen. However, the best parameters for the Central East Coast area of the United States may not be the best for other geographical areas. Future studies will be extended to other areas and to improving the models. Other weather elements are under study at the present time.

Table 26. Nine-Station Median Relative Frequency of Each Visibility Category for Each Hour of the Day

Hour	Winter Category				Summer Category			
(LST)	≤ .25	≤ 3	≤ 5	≥ 10	≤ 1	≤ 3	≥ 5	≤ 10
00	.0162	.134	.808	.577	.00752	.0585	.890	.489
01	.0179	.138	.805	.560	.00920	.0778	.876	.459
02	.0205	.140	.807	.561	.0142	.0911	.850	.426
03	.0231	.138	.813	.556	.0209	.123	.818	.389
04	.0214	.138	.807	.543	.0359	.151	.777	.364
05	.0273	.150	.806	.530	.0602	.207	.705	.303
06	.0248	.156	.793	.508	.0619	.231	.685	.308
07	.0273	.212	.726	.424	.0518	.211	.691	.324
08	.0273	.233	.689	.378	.0251	.157	.756	.348
09	.0188	.238	.688	.386	.0109	.120	.828	.385
10	.0162	.217	.716	.425	.00836	.0970	.854	.454
11	.0120	.185	.761	.493	.00502	.0694	.895	.515
12	.0102	.173	.783	.544	.00418	.0535	.912	.548
13	.00940	.155	.810	.572	.00418	.0502	.918	.574
14	.00855	.144	.820	.589	.00334	.0502	.927	.592
15	.00940	.149	.820	.600	.00418	.0485	.926	.598
16	.00120	.148	.816	.591	.00418	.0460	.928	.598
17	.00855	.147	.815	.552	.00502	.0426	.932	.604
18	.0102	.120	.838	.562	.00502	.0485	.915	.599
19	.0102	.116	.843	.579	.00585	.0602	.901	.553
20	.00940	.119	.843	.592	.00585	.0485	.912	.528
21	.0120	.127	.832	.592	.00418	.0426	.914	.551
22	.0154	.128	.827	.588	.00418	.0493	.909	.529
23	.0154	.138	.823	.579	.00585	.0518	.903	.520

Table 27. The "a'" Values Used in Eq. (15) to Find the Curves Shown in Figures 8 to 11

	Visibility Category			
Season	GE 10	GE 5	LE 3	LE 0.25 (Winter) LE 1.00 (Summer
Winter	0.158	0.224	0.260	0.425
Summer	0.163	0.175	0.263	0.524

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